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DISSERTATION

An Analysis of Military and Commercial Microelectronics: Has DoD's R&D Funding Had the Desired Effect?

Anna Slomovic

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Anna Slomovic

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The original version of this study was prepared as a dissertation in February 1991 in partial fulfillment of the requirements of the doctoral degree in public policy analysis at the RAND Graduate School. The faculty committee that supervised and approved the dissertation consisted of George L. Donohue (Chairman), Stephen M. Drezner, and Michael Kennedy.

PREFACE

This research is an analysis of the military research and development (R&D) investment strategy in microelectronics. The period examined is the decade of the 1980s, a time when the military tried to remedy a perceived gap between the state of the art in commercial and military microelectronics through a massive infusion of semiconductor R&D funds. The research looked at integrated circuits available for commercial and military applications, and used the comparison to evaluate the R&D investment strategy that led to the outcomes. The judgement about the past was used as a way of assessing the present and future R&D investment strategies.

The research was supported by the U.S. Army and the U.S. Air Force as part of their concept formulation efforts. This document has been accepted by the RAND Graduate School in partial satisfaction of requirements for its degree of Doctor of Philosophy in public policy analysis.

SUMMARY

The analysis presented in this dissertation is used to evaluate the effectiveness of semiconductor R&D policies followed by the U.S. military during the 1980s, and to make suggestions for improvements.

The semiconductor or microelectronics industry, i.e., U.S. ability to design and manufacture advanced integrated circuits (ICs) from semiconducting materials, is often called the foundation of the information age. The health of this industry has been of concern to industry observers and policymakers for the past several years in view of increasing competition from abroad and the perceived decline of worldwide U.S. market share as a result of this competition. The difficulties of the semiconductor industry are considered serious not only because the nation's future ability to compete in a variety of markets is seen as dependent on its success in semiconductor manufacturing, but also because U.S. defense policy rests on the qualitative superiority of U.S. weapons systems, which, in turn, rests on the superiority of the electronics incorporated in these systems.

The government, and especially the Department of Defense, has played a significant role in the development of the semiconductor industry and in funding research and development (R&D). During the industry's early days, the military not only funded advanced R&D, but took immediate advantage of ideas developed by companies. NASA and the military stood as first buyers of advanced semiconductor products. This early role as technology leader has influenced the military's attitude toward R&D funding and product development. The reversal in the relative technological position between the commercial industry and the military does not seem to have had much effect on the way the military funded semiconductor R&D in the 1980s.

The vast majority of money spent on microelectronics R&D in the past decade has been spent by commercial semiconductor firms on R&D related to commercial markets. The R&D funding provided by the government during this period was provided either for basic research or for products and processes of interest to the government. The avowed purpose of this funding was to improve performance and availability of advanced military microelectronics. The major government semiconductor R&D program during the past decade was the VHSIC Program, specifically structured with systems contractors as primes, and designed to advance semiconductor manufacturing technology by skipping generations.

Little coordination appears to have taken place between government-funded R&D and developments underway in commercial markets. In order to determine whether government R&D funding resulted in improved military microelectronics, this study compares military and commercial microcircuits in four product groups: general purpose microprocessors, digital signal processors, static random access memories, and programmable read-only memories. The study traces the development of each group of products over the past ten years and assesses the relative standing of commercial and military ICs within the group.

In order to structure the study, the industry is segmented in three ways: the markets are segmented into commercial and military; firm orientation is differentiated between systems and component focus; firm strategy is differentiated between technology leadership and followership. *Four hypotheses are posed and tested in this study.*

1. *Commercial markets can be expected to equal or lead military markets in the introduction of technologically advanced products.*
2. *The government's strategy of funding R&D intended to skip product generations does not produce advanced ICs faster than commercial evolutionary development.*
3. *Funding military microelectronics R&D through systems-oriented firms delays the creation of most advanced components because systems firms do not have improvement of components as a priority.*
4. *The government's preference for funding advanced product R&D precludes the government from taking advantage of low-cost circuits created by firms which choose the technology follower strategy.*

The data used in the study were collected from open sources. ICs are compared on the basis of density, speed, manufacturing technology, and price. In addition to the analysis of individual IC characteristics, a multivariate regression model is constructed for each product group to determine whether manufacturers within different segments of the industry perform different trade-offs between IC characteristics. The following results came out of the analysis of individual product groups.

Of the four stated hypotheses, the first two can be supported. The strongest support is for Hypothesis 2: there is no evidence that any of the components in either military or commercial markets skipped generations, regardless of R&D programs intended to produce this result. The single possible exception is the advanced DSP IC produced for VHSIC Phase 2. It is too early to judge, however, whether this IC can be

put into production quickly enough to allow its use in military systems before commercial systems catch up.

The degree to which the other hypotheses can be supported depends on the component in question. Except in the case of general purpose microprocessors in which commercial markets are dominant, the components introduced in commercial and military markets have similar capabilities. Commercial markets generally lead, but the differences are usually not significant in statistical analysis and not large when the individual component characteristics are examined. Prices for military components are generally higher, however. *This means that the military needs to consider its parity or slight lag vis à vis commercial markets when making R&D investments, and to focus these investments on translating commercial advances into military ICs.*

Support for Hypothesis 3 varies among components. While DSPs were significantly advanced by systems-oriented firms, there is no evidence that such was the case for any of the other three component groups considered in the study. While there is no strong support for Hypothesis 3 as stated, it is clearly not possible to say that systems-oriented firms develop more advanced components because of systems considerations. In fact, in the majority of cases they produce either components which are on par with their component-oriented counterparts, or are slightly behind. *It is, therefore, more sensible to direct military R&D programs toward firms with potential future production capacity for ICs in question, rather than relying on systems-oriented firms to move the ICs into weapons systems.*

There is too little data to perform a reasonable test of the last hypothesis. In the only case in which it is possible to do so, the case of architecture leaders with respect to general purpose microprocessors, the hypothesis cannot be supported, probably because the demand in the market was sufficiently high to keep prices high for both leaders and followers.

Several other issues can be addressed as a result of the analysis. The first is whether the DoD should continue to fund R&D which advances the general state of the art in semiconductor technology. One of the major reasons for the apparent lack of success of the VHSIC Program is the planners' lack of accounting for the fact that government funding does not take place in a vacuum. Competition from abroad has provided the impetus for the industry's investment of tremendous resources in R&D in order to counteract the erosion of U.S. technological leadership. Commercial semiconductor R&D spending is several times as high as the government investment in semiconductor R&D during the same time period. *Given the DoD's lagging position, the*

trends indicating that it is unlikely to regain leadership, and the relative sizes of military and commercial markets, it does not make sense for the military to spend money on advancing the general state of the art. Now that the relative technological positions of commercial and military components have been reversed, this type of spending cannot be justified by potential "spin-offs" from military to commercial applications. *Rather, it is more sensible to address DoD funding to areas of special DoD interest, such as the development of radiation-tolerant components, and to focus on keeping up with commercial markets. It makes sense to institutionalize the process of "spin-on" from commercial to military applications--a process that is already taking place informally as demonstrated by the choice of popular commercial RISC processors as military standards.*

The view expressed here appears to be at odds with the views expressed by the advocates of DoD funding for "dual-use" technologies. "Dual-use" technologies are defined as those that can be used by both commercial and military markets and would lead to a closer integration of commercial and military economies. The argument in favor of DoD funding for such technologies is that such funding would advance the state of the art in weapons systems while simultaneously helping the U.S. semiconductor industry recapture its international primacy.

Actually, the conflict with this argument is less in whether the development of "dual-use" technologies should be subsidized by the government (there are well-developed economic arguments that justify the government's involvement in R&D funding which serves to improve the general state of knowledge), but in the role of the DoD as the agency that takes a leading role in such funding. The DoD is no longer in the position of major beneficiary and first customer for advanced IC technology. Its resources are limited. Therefore, it appears more sensible to focus DoD's R&D on technologies which are important for national defense, including the translation of commercial advances into military uses, and address the issues of national competitiveness in a different manner.

This argument has direct bearing on the DoD's participation in the Sematech consortium. It is too early to judge whether Sematech is, indeed, the means by which the U.S. semiconductor industry will achieve worldwide semiconductor manufacturing leadership, the early stated goal of the consortium. Sematech's major achievement to date is a closer relationship between semiconductor manufacturers and manufacturers of semiconductor manufacturing equipment. While this is a laudable achievement which is likely to have positive long-term consequences for the U.S. manufacturing base, it is not

clear that the government's $100 million per year contribution (approximately 50 percent of the consortium's operating funds) should be channeled through the DoD, in view of the general nature of the consortium's goals.

The second issue deals with the general assumption that systems considerations will result in advanced components. This assumption does not hold in either military or commercial markets. When observers focus on the high cost of military systems, they often note that the firms which participate in the military market either do not participate in the commercial market, or do so with divisions which are separate from their military divisions. Given the very high and increasing cost of building and maintaining semiconductor manufacturing facilities, and given the increasing microelectronics content of weapons systems, it is not surprising that costs of weapons systems grow as long as firms which produce military ICs are not in the business of mass-producing ICs. *If the costs of weapons systems are to be contained, the electronics must be produced by firms which have incentives and opportunities to reduce the cost of ICs. As this study demonstrates, in the majority of cases the DoD is not getting more advanced components for the higher prices it pays.*

Greater use of commercial components in military applications has been urged in previous studies. This study took a different approach, but ended up with conclusions that support the earlier work. In most instances, commercial components lead their military counterparts, whether or not such leads are statistically significant. Reliability, temperature tolerance, and radiation tolerance of commercial components have increased over time, and have often been "tested" by the marketplace. In cases where there is a delay in the introduction of military components, it is often caused by additional military requirements for packaging and testing which must be met to translate commercial components into military ones. If these requirements can be relaxed, the DoD would be able to take greater advantage of the current state of the art.

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This study would not have come into existence without the help and support of colleagues, friends, and family. My greatest debt is to my dissertation committee. Their gifts of time, energy, and faith in the success of the enterprise created an environment in which I could learn and grow. George Donohue provided the inspiration for this study throughout its performance. As befits his title of committee chairman, he also made sure that a proper amount of perspiration was present at all times. Steve Drezner has been friend, supporter, and advisor from the day I came to RAND. His insights and his talent for sending my thinking along new tracks were invaluable. Mike Kennedy's questions and suggestions helped me make the story more coherent and convincing. I thank all three of you. Although your words did not always elicit agreement, they always inspired thought, and that, after all, is the essence of education.

I also thank those in industry and government who agreed to be interviewed for this study. I cannot identify them here, but can say that I have enjoyed the interaction. I hope that this work fairly reflects your thoughts and comments.

Several colleagues at RAND provided help and advice. Frank Camm helped me focus my questions and hone my arguments. Jim Hodges and John Adams helped me cope with the statistical analysis. The RAND library staff patiently and competently helped with my unreasonable requests in the search for data.

Friends and family provided the emotional support I required throughout the dissertation process. Many of them have had a dissertation experience of their own, or were having one right along with me. Their comments and suggestions were peer review in the best sense of the phrase.

Of course, all errors and omissions are mine alone.

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FIGURES

TABLES

ABBREVIATIONS

Symbol	Definition
ALU	Arithmetic logic unit
ASIC	Application-specific integrated circuit
CISC	Complex-instruction-set computing
CMOS	Complementary metal-oxide silicon
CPU	Central processing unit
DoD	Department of Defense
DARPA	Defense Advanced Research Projects Agency
DRAM	Dynamic random-access memory
DSP	Digital signal processor
ECL	Emitter-coupled logic
EPROM	Erasable programmable read-only memory
E^2PROM or EEPROM	Electrically-erasable programmable read-only memory
FET	Field effect transistor
FFT	Fast Fourier transform
FPU	Floating-point processing unit
GaAs	Gallium Arsenide
HDTV	High-definition television
IC	Integrated circuit
ISSCC	International Solid State Circuit Conference
MIPS	Millions of instructions per second
MMIC	Microwave Monolithic Integrated Circuit
MMU	Memory management unit
PROM	Programmable read-only memory
R&D	Research and development
RAM	Random-access memory
RISC	Reduced-instruction-set computing
ROM	Read-only memory
SOS	Silicon-on-sapphire
SRAM	Static random-access memory
TTL	Transistor-transistor logic

VHSIC	Very High Speed Integrated Circuits
VLSI	Very Large Scale Integration

I. INTRODUCTION

The microelectronics industry, i.e., U.S. ability to design and manufacture advanced integrated circuits from semiconducting materials, is often called the foundation of the information age. The health of this industry and the health of the upstream and downstream industries it supports[1] have been of concern to industry observers and policymakers for the past several years in view of increasing competition from abroad, especially from Asia. The press has carried statistics showing the decline of world market share attributed to U.S. manufacturers. Various government bodies have performed studies showing that the industry is in danger of decline or obliteration because of competition from abroad. The industry itself has been active in the political process by lobbying for legislation which curbs the practices of its international competitors in U.S. markets, insures market share for U.S. firms in other countries, and eases anti-trust restrictions on cooperation within the United States.

The difficulties of the semiconductor industry are considered serious not only because the nation's future ability to compete in a variety of markets is seen as dependent on its success in semiconductor manufacturing, but also because U.S. defense policy rests on the qualitative superiority of U.S. weapons systems. U.S. defense posture since World War II has been based on a relatively small military, equipped with a relatively small number of "smart" weapons, i.e., weapons which rely on microelectronics as a means of performing complex tasks. When supported by massive information processing, command, control, communications, and intelligence networks, made possible by advanced microelectronics, such a small military can be superior to a numerically larger opponent who is not equally well equipped. There is a strong perception that if the U.S. semiconductor industry is weakened, or if it loses its technological superiority, U.S. military posture will suffer because of the inability of the military to acquire the most advanced microelectronics for military systems.

Many solutions have been proposed to deal with the problem of perceived semiconductor industry decline, including greater use of government R&D funding to reduce the enormous and increasing expense of designing complex ICs and bringing them to production. The military, which has perceived itself as being particularly vulnerable in

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[1]Upstream industries include semiconductor manufacturing equipment, test equipment, and materials manufacturing. Downstream industries include a wide range of users of semiconductors, such as computers and communications equipment.

the last ten years, has attempted to improve its access to the most advanced semiconductor technology both directly and indirectly. The direct approach was exemplified by the development of weapons-relevant semiconductor products through major military R&D programs, such as the Very High Speed Integrated Circuit (VHSIC) Program and the Microwave Monolithic Integrated Circuit (MMIC) Program. The indirect approach, one that seeks to strengthen the industry as a whole and thereby assure the availability of a manufacturing base for military applications, is manifested in DoD's role as a partner in the Sematech consortium and in its support for research at universities.

The military's involvement in the semiconductor industry has a historical basis. Military need for small and reliable avionics is often cited as the deciding factor which provided the "pull" for the rapid development of the industry. The role of the government in those early stages, when it funded research and provided the market for semiconductor products, has been unanimously hailed as a great success. However, as the commercial markets have grown, the relative market power of the government declined in proportion to the government's market share. In the 1970s the military became concerned about the lag between military electronics and the electronics available in commercial products as firms concentrated on commercial markets and reduced their participation in military markets. This concern led to the initiation of the VHSIC Program, an R&D program which was supposed to advance the state of the art rapidly, using military integrated circuits (ICs) as test articles, and thereby providing the most advanced microcircuits for weapons systems. It is still too early for a final evaluation of the VHSIC Program's influence on military electronics, or on the industry as a whole. Early returns indicate, however, that the Program did not succeed in advancing the state of the art in microelectronics, or in improving the electronics content of military systems. Commercial markets have remained consistently ahead of military markets in the capabilities of microcircuits they produce. It is now often the case that instead of being "spun off" from military to commercial applications, advanced semiconductor technology is "spun on" from commercial to military applications.

One of the major reasons for the apparent lack of success of the VHSIC Program is the planners' failure to account for the fact that government funding does not take place in a vacuum. Competition from abroad has provided the impetus for the industry's investment of tremendous resources in R&D in order to counteract the erosion of U.S. technological leadership. The amount of money spent on R&D by the microelectronics industry over the past ten years has ranged between 9 percent and 15 percent of sales for

the merchant sector.[2] Microelectronics R&D spending by U.S. captives, thought to account for about a third of total U.S. IC production, is not included in the figure, but provides additional commercial funding. This commercial R&D spending is several times as high as the government investment in semiconductor R&D during the same time period.

For much of their history, the U.S. microelectronics manufacturers have dominated world markets. This began to change in the 1980s as Japanese manufacturers acquired a significant and growing presence in these markets. The U.S. microelectronics manufacturers have asked the government to intervene in the international competition on their behalf. They have lobbied for and won passage of protective trade legislation, and have established a government-industry research and development consortium, Sematech, with an express purpose of improving their ability to compete in international markets. Thus the government has assumed a new role: it is no longer only a provider of a specialized market that stimulates technological innovation, but also a direct participant in the commercial sector of the industry.

The vast majority of money spent on microelectronics R&D is spent by commercial semiconductor firms on R&D related to commercial markets. To date, the R&D funding provided by the government was provided either for basic research or for products and processes of interest to the government. In order to evaluate the impact that this funding has had on the state of the art, this study compares military and commercial microcircuits in four product groups: general-purpose microprocessors, digital signal processors, static random access memories, and programmable read-only memories. The study traces the development of each group of products over the past ten years and assesses the relative standing of commercial and military ICs within the group. The purpose of the analysis is to evaluate the effectiveness of past R&D policies followed by the military, and to make suggestions for future improvements.

Several important problems facing the semiconductor industry are not being addressed in this research. With the advent of Very Large Scale Integration (VLSI), the microelectronics industry is experiencing the need for large capital investment which has

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[2]The U.S. industry consists of a continuum of firms ranging from "merchant" to "captive." Pure merchant producers sell all their output on the open market. Pure captive producers are vertically integrated systems manufacturers which produce chips only for use in their own products. Many firms are not exclusively merchants or captives, but one or the other mode of operation predominates. This distinction has no meaning in Japan, where all firms produce ICs both for their own use and for sale in the open market.

to be turned over every three to four years.[3] Production plants are becoming more expensive as feature size goes down due to greater requirements for purity of materials and fabrication environment, more expensive technologies, and more complex designs. Many observers see the need for enormous capital investment and turnover as The Major Problem in the industry. R&D, on the other hand, has historically been perceived as healthy. That is, the United States can design anything and make a prototype, but has much less success than its foreign competitors, especially the Japanese, in manufacturing products on a mass scale. Mass production of integrated circuits is the place where large capital investment is required, hence the concern about cost of capital. This is a particular concern for the semiconductor industry because it is characterized by steep learning curves and significant economies of scale. As problematic as these issues are, however, capital formation and associated issues will not be addressed in this study. Neither will the issue of global competition and the way in which this competition should be approached.

The remainder of this Note proceeds as follows. Section II contains a derivation of the hypotheses and methodology for the study. Section III presents a brief history of the microelectronics industry. This history is by no means comprehensive; the emphasis is on the way R&D spending has been used as an instrument of policy. Sections IV through VII include the component-level analyses and their findings. The final section presents conclusions and policy implications of the research. Technical information on fabrication of integrated circuits and various IC technologies mentioned in the study is presented in Appendix A in order not to interrupt the flow of the narrative. A more detailed history of microprocessors is presented in Appendix B. The data used in the analysis can be found in Appendices C through F. Appendix G is a more detailed explanation of the statistics found in the text.

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[3]Rapid turn-over of capital is caused by the short life-times of semiconductor technology. New generations of ICs, often entering production three or four years after earlier generations, usually require improvements in manufacturing technology which cause obsolescence in manufacturing equipment, and sometimes complete refurbishment of fabrication facilities. This issue is further discussed in Appendix A.

II. HYPOTHESIS FORMULATION AND ANALYSIS METHODOLOGY

THE POLICY QUESTION

The military's role in the early history of the microelectronics industry was critical to the development of the industry. The military was not only the technology leader, but provided markets which motivated the industry to develop products with military applications.[1] However, the importance of military markets has declined as commercial markets expanded much faster. Between the 1960s and the 1980s, the military's share of integrated circuit purchases fell from about 100 percent[2] to less than 10 percent.[3] With declining market share came the decline in the influence which the military can exercise over the kinds of products and processes developed by the industry. Despite the problems inherent in such a situation, it also provides an opportunity for military purchasers of microelectronic products: since commercial markets are much larger than military markets, and since large R&D investments are required in commercial markets, the DoD should be able to use commercial R&D as a basis for investment in military microelectronics. This research addresses the following question. *How can the government investment strategy in military microelectronics R&D be improved to take advantage of the operation of firms in commercial markets?* This question is addressed by looking at the way government R&D is funded, and by comparing military and commercial microelectronics products on the market to determine the effectiveness of this funding.

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[1]Let me introduce some fundamental definitions at this point. "Product" or "component" is defined as a device made of semiconducting material, capable of storing or manipulating information. Microelectronic devices are classified in various ways, shown in Appendix A. Several related products which perform similar functions and span a range of performance characteristics are defined as a product family. "Product-related" activities are those which improve the design or performance characteristics of a product or product family. "Process-related" activities are activities which relate to the production process, and may be used for the production of different products or product families.

Microelectronic products cannot operate by themselves. The products discussed in this document are components of larger systems in which components are integrated for the performance of a specific task.

[2]R.C. Levin, "The Semiconductor Industry" in *Government and Technical Progress*, R.R. Nelson, ed., Pergamon Press, New York, 1982, p. 63.

[3]K. Julian, "Defense Program Pushes Microchip Frontiers," *High Technology*, May 1985, p. 56.

There are many semiconductor-related technologies which are potentially of interest to the government and so are potential candidates for government-funded research. However, available investment resources are limited. R&D managers must, therefore, make their investments in ways that create maximum military capability for the money invested. A sensible government investment strategy is to fund those technologies which are particularly important for military applications but are not likely to appear along the evolutionary path of commercial technology. It is also sensible to reduce funding of those products and technologies which are likely to develop without government intervention because industry considers them essential. A possible exception to the latter is a small amount of funding used as a hedge against industry decision to abandon or slow down a particular technological approach.

The government is interested not only in technology itself, but also in the length of time before it becomes available to the military for incorporation into weapons systems. The U.S. defense posture relies heavily on the qualitative superiority of a relatively small number of weapons, and much of this superiority is derived from the superior electronics carried by the weapons platforms.[4] Timing of introduction is, therefore, an important dimension of government investment strategy in microelectronics R&D.

As will be discussed in greater detail in Section III, for more than ten years the government has funded microelectronics R&D mainly through weapons systems contractors. Table 2.1 shows a list of the top 20 defense electronics contractors from 1983 to 1989.[5] Many of these firms have capabilities for producing some microcircuits for their own systems; many of them have participated in government microelectronics R&D contracts. With the exception of Texas Instruments and IBM, however, they are not in the business of mass-producing integrated circuits (ICs), and IBM produces ICs strictly for internal consumption. Only Texas Instruments (TI) is a major supplier of semiconductors to other firms for both commercial and military applications. Other large IC suppliers appearing on the Top 100 Defense Electronics Contractors list are Advanced Micro Devices (No. 55 in 1983; No. 85 in 1989), Intel (No. 72 in 1986, not on the list in 1983 or in 1989), Motorola (No. 27 in 1983; No. 40 in 1989), and National Semiconductor (No. 52 in 1983; No. 68 in 1989).

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[4] *Discriminate Deterrence*, among others.

[5] *Defense Electronics* magazine, the compiler of the list of the Top 100 Defense Electronics Contractors, defined "electronics" as electrically-activated hardware, such as computers, individual components, circuit boards, radar and guidance systems, avionics, electro-optics, etc. Foreign contractors were included in the list for the first time in 1988.

The largest systems contractors are also the largest recipients of government R&D funding. In 1983, 1985, and 1987, there were 13, 14, and 11 firms, respectively, which appeared on the list of the top 20 defense electronics contractors and among the top 20 recipients of government R&D contracts in terms of dollar volume.[6] If non-profit and educational institutions are removed from the list of top 20 R&D funding recipients, the correlation is even higher.

Table 2.1

TOP 20 DEFENSE ELECTRONICS FIRMS

Rank	1983	1985	1987	1989
1	Hughes A/C	Hughes A/C	General Motors	GM/Hughes
2	Lockheed	Lockheed	Lockheed	GE/RCA
3	Raytheon	Raytheon	Raytheon	Raytheon
4	Rockwell Int'l	Sperry	GE/RCA	Thomson CSF
5	General Electric	Litton	Boeing	GEC
6	Sperry	General Electric	Unisys	Lockheed
7	IBM	TRW	TRW	TRW
8	TRW	Boeing	Westinghouse	Unisys
9	RCA	Honeywell	Rockwell	Litton
10	Westinghouse	Ford Aerospace	Litton	Martin Marietta
11	Honeywell	IBM	Martin Marietta	Westinghouse
12	ITT	Texas Instruments	Allied Signal	Rockwell
13	Texas Instruments	Rockwell	Honeywell	Texas Instruments
14	General Dynamics	RCA	IBM	IBM
15	Boeing	Westinghouse	General Dynamics	Daimler
16	Ford Aerospace	Martin Marietta	Texas Instruments	Plessey
17	Martin Marietta	AVCO	Ford Aerospace	E-Systems
18	Litton	ITT	ITT	Philips
19	McDonnell Douglas	General Dynamics	Singer	ITT
20	Grumman	McDonnell Douglas	Harris	General Dynamics

SOURCE: *Defense Electronics*, 1983-1990.

Major open-market semiconductor suppliers which appear on the list of top 500 recipients of DoD RDT&E funding are Motorola (No. 39 in 1983; No. 42 in 1987) and Texas Instruments (No. 44 in 1983, No. 36 in 1987). Intel, Advanced Micro Devices, and National Semiconductor do not appear among the top 500 institutions receiving defense RDT&E funding--if they receive any R&D funding from the government, the amount is less than approximately $1 million to $1.5 million per year, the smallest amounts received

[6] Directorate for Information, Operations and Reports, *500 Contractors Receiving the Largest Dollar Volume of Prime Contract Awards for RDT&E*, The Pentagon, Washington, D.C., 1982-1987.

by institutions on the list. Both Motorola and Texas Instruments have major military systems programs, and both participated in the DoD VHSIC Program, but it is difficult to say how much of defense contract R&D they receive is relevant to systems work and how much to the development of microelectronic components.[7]

The high degree of correlation between recipients of government R&D funding and a list of systems contractors is deliberate. Both the VHSIC Program and the MMIC Program were structured specifically to use systems contractors as primes and to encourage them to team with component producers. It was reasoned that funding IC development through systems contractors would speed the incorporation of advanced electronics into the weapons systems produced by the same contractors. The efficacy of this approach has been disputed. Critics have said that systems contractors have concentrated on system design and underestimated the effort required to actually create chips, and that this has led to schedule slips and frictions within design teams.[8] This analysis is intended to provide some structure and data which can be used to evaluate the strategy of developing ICs through systems contractors.

Evaluating an R&D investment strategy involves dealing with two sets of issues: which technologies should be funded, and which parts of the industry should be recipients of the funding. Let us examine the logical underpinning of each of these sets of issues.

Technologies That Should Be Funded

If a technology is of interest to the commercial market, i.e., if firms see an opportunity for making a profit from developing a particular product or process, it is likely to be developed without government intervention.[9] However, due to the specialized nature of military equipment, the military may have unusual technological requirements. For instance, both commercial and military communication satellites require radiation-tolerant (rad-hard) ICs because space is a radiation-filled environment, but the ICs for military satellites must meet additional requirements related to their

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[7]Interviews indicate that Motorola does not use much of its government-funded R&D for IC work. It was, however, a subcontractor to TRW on a $34.6 million VHSIC Phase 1 contract and a $60 million Phase 2 contract. Motorola has a major presence in military markets through systems and subsystems sales, and most government R&D funding it receives is related to that. TI, on the other hand, has made a significant commitment to the military microcircuits market and uses both contract R&D funds and IR&D funds for R&D relevant to this market. TI had a $22.7 million VHSIC Phase 1 contract, but was not selected for Phase 2.

[8]L. Brueckner and M. Borrus, *Assessing the Commercial Impact of the VHSIC Program*, December 1984, p. 50ff.

[9]I am assuming no market failures for the moment. I am not assuming that the technology will be developed on a schedule acceptable to the government.

special missions. Some technologies may, therefore, be of interest to the government but not to commercial markets. The military needs to fund the development of such technologies if it appears that commercial suppliers will be unable or unwilling to meet military performance parameters through their own R&D investment.

Some technologies or performance parameters may be of greater interest to the government than to the commercial markets, although both markets are likely to benefit from products having similar characteristics. This category includes ICs which can operate in various hostile environments, e.g., within a wide temperature range. The government may wish to supplement industry's funding of R&D related to such technologies either to assure development, to assure development on a faster-than-otherwise-likely schedule, or to provide hedging against failure of (and industry disillusionment with) approaches under exploration.

Parts of the Industry That Should Be Funded

In addition to understanding what to fund, the government R&D investor must also understand where the funds should be invested in a way that would be likely to create a production capability. Some firms or divisions of firms are not in the business of volume production of microelectronic components, and may be willing to accept government contracts without having subsequent production of parts as a goal.[10] These firms may fulfill the requirements of a government R&D contract, but they have little interest in transferring the results to production.

This creates several potential problems. It is never easy to transfer the results of completed R&D into production, especially when R&D and production are separated by organizational barriers. When one firm performs R&D and another firm is used as a source of production, the R&D transfer problem is exacerbated.[11] Also, people who perform R&D without an eye toward production may not pay sufficient attention to potential production problems which can be prevented or reduced through design and development efforts specifically directed toward that end.[12] This, in turn, results in high unit costs for the circuits produced.

Therefore, it is not only important for the government to invest in the right technologies, but to invest in those parts of the industry which are likely to be volume

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[10]Conversation with L. Steele. It is not unusual for government contracts to specify deliverables as several test circuits, without any indication of or commitment to future production.

[11]L. Steele, op. cit., pp. 157ff.

[12]R. Gomory, "From the 'Ladder of Science' To the Product Development Cycle," *Harvard Business Review*, p. 103.

producers of ICs. This is particularly important in the industry which exhibits steep learning curves and economies of scale.

RESEARCH STRATEGY

This study approaches the question of government investment in microelectronics R&D by examining important factors in the structure of the industry and its markets, the way these factors influence the industry's decision-making and the resulting products and processes. The research involves the following steps.

1. A taxonomy of the industry is created. This is a structure within which firms and their products are classified.
2. Four groups of products are examined, and a first cut is made at connecting firm characteristics with the attributes of products created. Technical product attributes of interest are compared with the timing of introduction in different segments of the market. This part of the research evaluates the contribution of government and commercial R&D to the state of the art in the product groups studied.
3. The current government investment strategy is re-evaluated in view of the technology classification and product group studies. Implications can be drawn out by considering the likely directions to be taken by industry, decision-making processes of government and industry, and the government's technical requirements.

Let me now construct a taxonomy of the industry, put forth some hypotheses, and present a research methodology used for testing the hypotheses.

A Taxonomy of the Industry

The microelectronics industry is not homogeneous. Differences between firms (or independent divisions of multidivisional firms) can be classified along three dimensions, shown in Figure 1. All the boundaries shown in the figure are "semipermeable" and somewhat artificial to help structure the analysis. Some firms operate in more than one part of the industry as it is segmented.

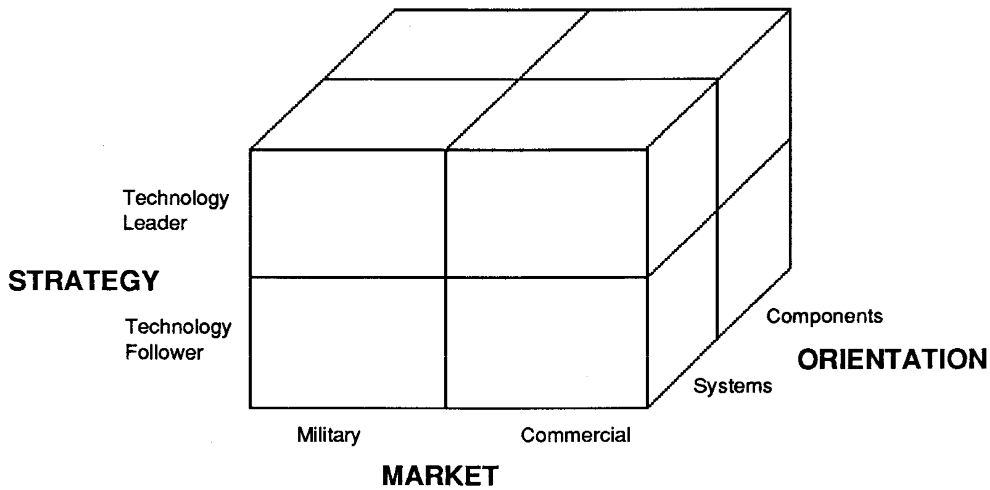

Fig. 1--Dimensions of differences in the microelectronics industry

The distinction between *commercial and military markets* is fairly clear: it is arrived at by identifying the firm's ultimate customer. Given the flow-down provisions of government contracts,[13] it is possible to determine the ultimate destination of systems and components even in cases where the product goes through several intermediate customers. Additionally, microelectronic components designed for military markets must undergo testing and qualification in accordance with military standards, and firms which sell to the military or military contractors differentiate their military components from those destined for commercial markets. The distinction between *systems- and component-oriented firms* is based on the place of the firm in the production chain. A decision to compete at the component level requires a different approach to technology than a decision to compete at the systems level. The choice of *strategy* reflects both the firm's internal environment and its approach to its markets. A firm that chooses the technology leader strategy offers a product technologically different (usually more advanced along some dimension) from one offered by its competitors; a firm which

[13]"Flow-down provisions" of government contracts are clauses from prime contracts which contractors must include in their subcontracts and purchase orders. These provisions are identified in the government procurement regulations, and often passed from the highest to the lowest contract level.

chooses the technology follower strategy offers a product similar to one offered by the competition but different along some non-technological dimension, such as lower price.

Each of these dimensions and its impact on the firm's R&D portfolio is discussed in greater detail below, starting with the distinction between commercial and military markets.

Differences Between Commercial and Military Markets

Table 2.2[14] summarizes the significant differences between commercial and military microelectronics. The military, constrained more by space, weight, and power requirements than by costs, is looking for products which would optimize mission performance for its systems. It requires few circuits compared to the commercial markets, and pays for them based on its ability to regulate contractors. Firms or divisions of firms which sell mainly to commercial or military markets have incentives to develop different technologies and to perform their R&D differently, depending on the market which is their main focus.

Table 2.2

COMMERCIAL AND MILITARY MICROELECTRONICS--A COMPARISON

COMMERCIAL MICROELECTRONICS	MILITARY MICROELECTRONICS
Short product lifetime	Long product lifetime
Large scale production	Small scale production
Standardized products	Customized products
Cost emphasis	Performance emphasis
Price determined by market	Price determined through regulation

The most obvious explanation for the differences between military and commercial microelectronics and for the differences in relevant R&D, is the difference in products themselves, as dictated by the purposes of the equipment into which ICs are incorporated and the environments in which the equipment must operate. The military has required the invention of ICs specifically for military applications, but even in cases where the function of the circuits is the same in commercial and military equipment, military

[14]The table is derived from a variety of reports and articles which deal with commercial and military microelectronics.

specifications require ICs to operate in a broader temperature range than their commercial counterparts. The temperature range for military applications is specified as -55°C to +125°C versus 0°C to 70°C for standard commercial ICs and -40°C to +85°C for rugged industrial ICs. The broader temperature range leads suppliers to create new packaging for military circuits, although alterations in the circuits themselves are generally not necessary with current technology. Many military ICs are also required to be radiation-tolerant, which requires implementation of circuits with different technologies than those used for non-rad-hard parts (e.g., silicon-on-sapphire or gallium arsenide).

Other factors which differentiate commercial from military markets are differences in product lifetimes and in the length of the R&D cycle. While commercial electronic systems have a half-life of about four years,[15] some military systems may operate for 20 years or longer, and must be supplied with the same ICs throughout their lifetime.[16] The design cycle for military systems is quite long as well--sometimes as long as 10 years from design to introduction in the field. This long design cycle at the systems level often leads the government to attempt to skip several generations ahead of the current state of the art so that by the time the systems are fielded, their electronics will be modernized to the same extent as the platforms themselves. This creates a possibility that government-sponsored R&D is concerned with technologies in a different part of the technology life-cycle than those which the firm finds most useful at any given time.[17] All these factors make it difficult for firms to use the same R&D efforts for products sold in commercial and military markets.

Even in cases where the same products would serve both markets, firms often separate their government-funded R&D from internally funded efforts because of the differences in the structure of commercial and military markets. This, too, has an impact on the kind of R&D relevant to the two markets.

The commercial microelectronics market is characterized by multiple buyers and sellers. Classes of products, such as SRAMs or microprocessors, are usually produced by several firms, even though the market is not perfectly competitive. The government market, on the other hand, is characterized by few buyers backed by legislative power. As a sole purchaser of selected goods and services, the government has power vis à vis

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[15]E.D. Maynard, *VHSIC Annual Report for 1986*, p. 11.

[16]*VHSIC Annual Report for 1987*, draft, p. 78

[17]Interviews are the source for this statement. For example, the Air Force had decided that producing rad-hard DRAMs based on perfectly adequate current technology was not adventurous enough and insisted that more advanced technology be developed.

sellers, just as any purchaser would in a similar position. When the government faces a group of competing sellers, the power of monopsony allows it to have control over the conditions of sale, such as product attributes and prices.

The government also has the power to pass legislation which forces firms to comply with government requirements even in cases where a firm has sufficient power vis à vis the government to change the terms of the agreement, i.e., in cases where the government faces a "sole source" with respect to a specific product. This combination of monopsony power and legislative authority make the government market different from commercial markets.[18] The need to comply with government regulations often makes it difficult for firms which are oriented toward commercial markets to produce ICs for the military.

Differences Between Systems and Component Orientation

Figure 2[19] shows a simple view of the production chain from natural resources to final customer. Firms may choose to build and emphasize capabilities contained in one or more of the boxes shown--vertically integrated firms may manufacture some or all of the components they use in their systems. Usually, however, firms choose primarily one spot which dominates the way in which they think of themselves. The point in the production cycle at which the firm chooses to compete determines its approach to technology-related activities.

Firms in the U.S. semiconductor industry are classified according to their place within the production chain; a distinction is made between "merchant" and "captive" suppliers. "Merchant" suppliers are firms which sell ICs on the open market. These are generally component-oriented firms, although some firms also have divisions that produce systems using a part of the firm's IC production. Good examples of component-oriented firms in this context are Intel, Motorola, and Texas Instruments. Merchant producers, competing at the component level as providers of integrated circuits,

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[18]This is not meant to imply that government regulations are capricious. The recent OTA report on the technology base, *Holding the Edge*, listed the government's goals in the procurement process. One of those goals was efficient procurement, but there were others, some of them in conflict with that goal. Government procurement goals include small and minority business access to government contracts, fairness in competition and maintaining multiple sources as surge reserve. The primary motivation for many of the financial and accounting regulations is assuring that taxpayers' money is properly spent. This multiplicity of potentially conflicting goals differentiates government procurement from the commercial process in which creating maximum profitability dominates.

[19]This figure is adapted from Figure 3.1 in L. Steele, op. cit., p. 77.

emphasize the unique attributes of their chips, warrant performance, price, and life, but do not assume the responsibility for the eventual use or the utility of their products in solving the customer's problems.

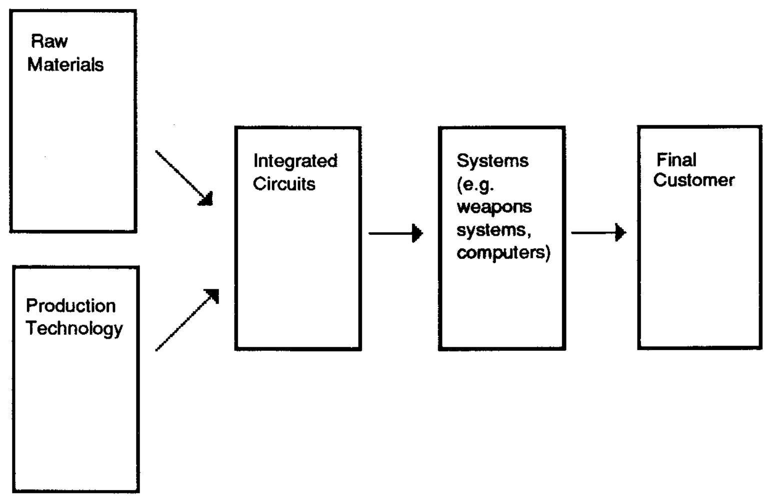

Fig. 2--Production chain

"Captive" suppliers are firms which produce ICs for use in their own systems. Probably the best example of a captive is IBM, one of the largest IC producers in the world. Although IBM buys ICs on the open market when its internal production is insufficient to meet its needs or when it does not produce a particular IC, the firm does not sell ICs to other firms. Other U.S. captives include Hewlett-Packard and, to a lesser extent since deregulation, AT&T. Systems suppliers emphasize the firm's ability to meet customers' needs by integrating components into systems. This difference in outlook leads to a different emphasis within the firm's technology-related activities.[20]

Component-oriented companies rely primarily on advances in performance to provide unique product attributes or to reduce cost. Each component is designed individually for versatility and maximum performance so that it could be integrated into as many systems as possible. Component-oriented firms find it difficult to assemble and price systems because returns on systems are generally lower than the combined mark-ups on individual components designed in this way, and component-oriented firms or

[20]Because Japanese firms behave like merchant suppliers in U.S. markets, they are classified as component-oriented firms within this study.

business units have no way of allocating the reduced returns among the different components.[21] They also tend to be very conscious of the cost of their components and devote R&D resources to cost reduction because they compete with other component houses and sometimes with the internal production capabilities of systems houses as well.[22]

Systems-oriented firms, on the other hand, place greater emphasis on the understanding of customer requirements and on systems engineering to meet these needs. They often rely on components and technologies developed elsewhere, and pursue advanced technology less for its own sake than for its ability to meet specific customer needs.[23] They focus on compartmentalization and packaging, i.e., on ways to combine components into the best system or subsystem. Their concern is more with reliability and availability of components during the system lifetime than with cost of individual components.[24] Systems firms compete with other systems firms, and so have incentives to develop technology particularly suited to their systems. They also have incentives not to reveal their proprietary approaches to systems designs. For these reasons they generally do not like to serve as suppliers to their systems-level competitors.

This has the following implications for military markets. When weapons systems suppliers create ICs for incorporation into their systems, these ICs are likely to be optimized for the particular weapons system. This makes them even less optimal for other weapons systems, and further reduces the already low volumes of individual components produced for the military. It also increases the number and cost of military components in production.[25]

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[21]L. Steele, op. cit., p. 80.

[22]N. Hazewindus, *The U.S. Microelectronics Industry*, Pergamon Press, New York, 1982, p. 90.

[23]L. Steele, op. cit., pp. 78-82. An example of this difference in approach was seen in the VHSIC Program. Brueckner and Borrus and others have documented the frictions that resulted between systems firms, serving as primes, and merchant producers, serving as subcontractors, because of the differences in the emphasis and approach to R&D by two types of firms. [See, for instance, Brueckner and Borrus, pp. 50-51.]

[24]N. Hazewindus, op. cit, p. 91.

[25]The DSB report on the use of commercial components in military systems found that there are 77,500 source-control drawings (SCDs) for devices supplied by manufacturers of military ICs. In the majority of cases, these are ICs either created or modified by manufacturers and called out specifically for use in specific systems. By contrast, there are 1,475 generic devices qualified under MIL-STD-883 and 450 devices described by standard military drawings (SMDs). The DSB report blames proliferation of SCDs for the higher cost, constrained supply, and lower technology level of military ICs. [*Report of the DSB on Use of Commercial Components in Military Equipment*, pp. A-14 through A-16.]

Component-oriented firms may not produce chips which will result in optimum performance in any one weapons system, but may provide greater commonality between weapons systems. They also tend to focus on cost to a greater degree than systems firms since they do not have the flexibility of system-level profits to cushion fluctuation in component demand.

As discussed above, the military prefers to deal with systems firms. By comparing the components produced by firms with systems and component orientations, this study examines whether this is the best approach to achieving the most technologically advanced and cost-effective military electronics.

Differences in Market Strategies

Whether it competes at component or systems level, a firm can adopt one of two strategies: it can offer the most technologically advanced product on the market, or it can remain at the current level of technology in the industry and compete on non-technical attributes such as price, service, or delivery. A firm which produces the most technologically advanced products acquires a measure of monopoly power which allows it to charge premium prices. The high prices allow the firm to recover some of its R&D investment before imitators enter the market and cost becomes an important factor in the competition.

When captive producers of microelectronic components choose to compete as technology leaders, they choose attributes ranging from advanced technical capabilities to ease of operation as a way to differentiate their systems from the systems of their competitors. Merchant semiconductor suppliers usually choose improved IC performance characteristics, such as capacity and circuit speed, as their means of technology leadership. Improved circuit capabilities are so highly prized among merchants that being first to market with a circuit at a higher density or bit level results in the highest market share for the innovator even after the entry of competing devices into the market. Firms which adopt the technology leadership strategy sometimes choose to surrender their market share and move out of competition for a product when imitators enter the market and product cost becomes the dominant factor in the competition.[26]

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[26]Francis C. Spital's "Gaining Market Share Advantage in the Semiconductor Industry by Lead Time and Innovation," in Richard S. Rosenbloom, ed., *Research On Technological Innovation, Management and Policy*, Volume 1, JAI Press Inc., Greenwich, Connecticut, 1983, p. 65.

It is not uncommon for microelectronics firms to choose not to be technology leaders. Technology leadership is expensive and risky. Intel, a technology leader in microprocessors, spent $100 million in development costs on the 80386 microprocessor, and $250 million on its 80486,[27] and that at a time when its microprocessors were one of two standards in the industry. Few firms have such resources, and improvements in both product and process technology are becoming more and more costly with every new generation of microcircuits. Technology leadership also involves considerable risk--there is always a chance that a competitor will develop a product which will gain better acceptance in the market, supplanting the early entry as market leader. The risk is increased if being first to market means rushing development or compromising testing.

Many firms prefer to wait until another firm introduces the next generation of product or process technology and then either acquire a license or trade some of their technology in other areas for access to the advanced product or process.[28] Second-source arrangements are common in the microelectronics industry. There are three reasons for such agreements:

1. to assure the system manufacturer that adequate supply exists for a component which serves as the heart of the system manufacturer's system;
2. to attempt to establish an industry standard which could be made profitable for the technology leader through licensing agreements;
3. where necessary, to encourage the creation of a multiplicity of peripheral supporting devices which would take full advantage of the original device's capabilities.

In order to attract customers, second sources must offer something that the original sources either cannot or are not willing to offer. These may include a lower price or improved quality or delivery schedule. If the firm's products are approximately as good as those sold by the competition, lower price will translate directly into profitability because the firm is likely to take market share from other firms in the industry. Price wars, even between firms which have second-sourcing arrangements with each other, are not unknown.

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[27]C. Gottlieb, "Intel's Plan for Staying on Top," *Fortune*, March 27, 1989, p. 99. *Business Week*, September 26, 1988, puts the development cost for the 80486 at $300 million over 4 years.

[28]This latter strategy was successfully adopted by the Japanese when they were making early in-roads into U.S. semiconductor markets. The Japanese chose dynamic random access memory (DRAM) as their first product because it allowed them to exploit their advantages in low-cost manufacturing and to minimize their relative weakness in innovation. [W.F. Finan and A.M. LaMond, *Sustaining U.S. Competitiveness in Microelectronics*, p. 166.]

A firm does not have to participate in every segment of the market, or use the same strategy in every segment in which it participates. It can choose a specific set of customers with specific needs and be either a technology leader or technology follower in that particular segment. A "niche" supplier can employ the technology leadership strategy to supply a small number of units with specific characteristics when such small-scale production is considered inefficient by firms which rely on large scale production to supply the entire market. In his book, *Competitive Strategies*, Michael Porter states that if a firm chooses to follow different strategies in different market segments, it must strictly separate the business units engaged in different types of strategic behavior since the two approaches are basically incompatible.[29]

Choice of strategy leads to differences in the firm's choice of technology-related activities. A firm which chooses to be a technology follower uses its design area to copy designs and modify them, if possible, to improve producibility and reduce production cost. There is also need for speed and low cost of R&D to keep the overall product cost low. The emphasis in production-related R&D is on minimizing the number of production steps, maximizing line throughput, and increasing yield. Flexibility is important because, as a follower, the firm must be alert to new products appearing on the market--products which it must quickly imitate, improve upon if possible, and get into large-scale production.

The firm which chooses technology leadership must invest in creating new chip architectures and technologies which allow improvement in IC speeds and densities. It must invest not only in future generations of current products but in creating technologies which would serve as bases for new products. Systems suppliers which choose this strategy exhibit emphasis on optimizing designs for their current and future systems. Component-level merchants using the technology leader strategy exhibit emphasis on flexible designs which allow operation of chips in multiple systems in order to acquire design wins.[30] Technology leaders in components must have the capability to put chips into production quickly in order to take maximum advantage of pre-emption.

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[29]Michael Porter, *Competitive Strategies*, p. 18. Lowell Steele seems to agree with him, op. cit.

[30]A design win for a merchant semiconductor firm is a decision of its customer, a systems firm, to include the firm's IC in a system design.

Hypotheses for Analysis

When the question of government R&D investment strategy is considered in light of the theoretical structure presented above, several specific hypotheses can be posed and tested. Four hypotheses are presented below, one for each of the three dimensions of the structure, and one dealing with time, the fourth dimension not shown in Figure 1.

> *Hypothesis 1: commercial vs. military markets. Commercial markets can be expected to lead or equal military markets in the introduction of technologically advanced products.*

Firms can be expected to introduce advanced ICs in the commercial market either first or concurrently with the introduction in the military market. Short product lifetimes and the large size of the commercial market compared to the military market make the introduction of products in that market a priority. If military applications require modifications to commercial ICs, or if additional qualification procedures are required as a way of introducing commercial chips into the military market, firms would be willing to do this in an effort to acquire additional customers, but introduction into the commercial market will not be delayed to make it concurrent with the military market.

This hypothesis can be tested by noting the characteristics and timing of introduction of ICs into commercial and military markets. If commercial markets do, indeed, lead or equal military markets in introducing advanced products and processes, the current strategy of investing in advancing the state of the art through military R&D would be shown to be inappropriate. Rather, it would be more sensible for the military to concentrate on funding the transfer of technology from commercial into military microelectronics, and concentrating on funding areas in which military products differ from commercial products.

> *Hypothesis 2: evolutionary development strategy vs. skipping product generations. The government's strategy of skipping product generations does not produce advanced ICs faster than commercial evolutionary development.*

During the past decade, the government has sponsored R&D directed at products and technologies which are several generations ahead of next-generation commercial technologies. It is possible, however, that the attainment of such goals requires a

sufficiently long time so that the introduction of government-funded chips and commercially funded chips with similar capabilities occurs at about the same time. Attempts to skip several generations are usually expensive compared to evolutionary development, and may be a waste of resources if they do not produce advances ahead of normal evolutionary development. This hypothesis can be tested by comparing the timing of introduction of ICs with similar characteristics in commercial and military markets. ICs which resulted from the VHSIC Program are particularly interesting in this context.

> *Hypothesis 3: systems vs. components orientation. Funding military microelectronics R&D through systems-oriented firms delays the creation of most advanced components because systems firms do not have improvement of components as a priority.*

The government has used systems contractors as prime contractors of microelectronics R&D in order to speed insertion of advanced technologies into weapons systems. As we saw in the discussion of systems and component orientations, firms with a component orientation can be expected to introduce technological advances in chip performance faster than systems firms because chip-level performance is their primary concern.

This hypothesis can be tested by noting the characteristics and timing of introduction of ICs by systems- and component-oriented firms. If the hypothesis can be supported, it would imply that the government should shift its R&D investment from systems firms toward component firms in those instances where it requires advanced components. In addition to providing technical advances faster, this would provide the benefits of cross-weapons-systems similarity and larger production runs, which is likely, in turn, to result in lower cost of military microelectronics.

> *Hypothesis 4: technology leadership vs. cost followership. The government's preference for funding advanced product R&D precludes the government from taking advantage of low-cost circuits created by firms which choose the technology follower strategy.*

As noted above, historically the military has been constrained more by weight and power than by cost, and relied on small numbers of advanced weapons as a means of

meeting U.S. defense obligations. These factors encouraged the DoD to deal with firms which optimize weapons performance by use of the technology leadership strategy at the systems level. However, this approach to microelectronics R&D may be self-defeating because it leads to the creation of ICs which are even more expensive than they would be otherwise. Firms which use the technology follower strategy may produce ICs which have technical capabilities not much further behind those produced by technology leaders, but at much lower cost, and this may allow a greater number of weapons to be purchased.

This hypothesis can be tested by looking at the technical characteristics of products created by firms which use the technology leader and the technology follower strategies, and by noting the timing of introduction of such products in the relevant market segments. If it can be demonstrated that technology followers are not far behind technology leaders, it would imply that the government would save money by moving toward financing R&D by technology followers for translating commercial technological advances into military products.

When these hypotheses are taken as a group, they imply a different policy for government investment in microelectronics R&D from the policy which has been in effect during the 1980s. They imply that, except for narrow areas, the government should not invest in advancing the state of the art. The most advanced products will be developed in the commercial market because that market is much larger and much more profitable (Hypotheses 1 and 2). It is, therefore, sensible to concentrate on translating these advances into military markets rather than trying to compete with commercial markets. This can be done by relying on firms which have an interest in and capability for rapidly copying and improving component designs (Hypothesis 4). In those cases where the government requires advanced capabilities in areas not likely to be of interest to the commercial market, it should fund component-oriented firms which have IC improvement as their major goal and expertise (Hypothesis 3).

Let us now examine the research methodology used for gathering data and testing the hypotheses.

RESEARCH METHODOLOGY

The first step of the methodology, the creation of the taxonomy of the industry, was presented above. Let us now examine the other methodological steps in detail and look at the way they will elucidate the hypotheses advanced above.

Creation of the Database

Figure 3 shows a classification of microelectronic products by type. Of the four broad categories, this study addresses only one: integrated circuits. Memories, microprocessors, logic devices, analog and other ICs comprise approximately 76 percent of worldwide annual sales of the merchant industry.[31] ICs comprise 71 percent of total military semiconductor sales.[32] Within the integrated circuit category four specific groups of products are investigated: general purpose microprocessors, digital signal processors, static random access memories, and programmable read-only memories. These four product groups are chosen because they play important roles in both commercial and military markets. The figure also shows the portion of the market covered at each level of classification.[33] The results obtained by studying them can be generalized to other "dual-use" microelectronics products.

General purpose microprocessors are devices which perform a variety of arithmetic and logic tasks, specified by software, on data which are stored separately. The main use of these devices is as central processing units in computers, including mission computers in military systems. As these processors have become increasingly specialized, they have also spread into embedded control applications in everything from automobile engines to industrial machines.

Digital signal processors (DSPs) are simpler than general purpose microprocessors and optimized for performing arithmetic functions with great speed. The major use of DSPs is in processing data, often in real time, which are collected by analog sensors. Applications include radar, sonar, electronic surveillance, graphics, and image processing.

Static random-access memories (SRAMs) are memory devices which permit read and write operations by the user. Their chief attribute is very fast access to information. SRAMs are faster than DRAMs and used for applications in which fast memory access is important, such as cache memory in support of microprocessors.

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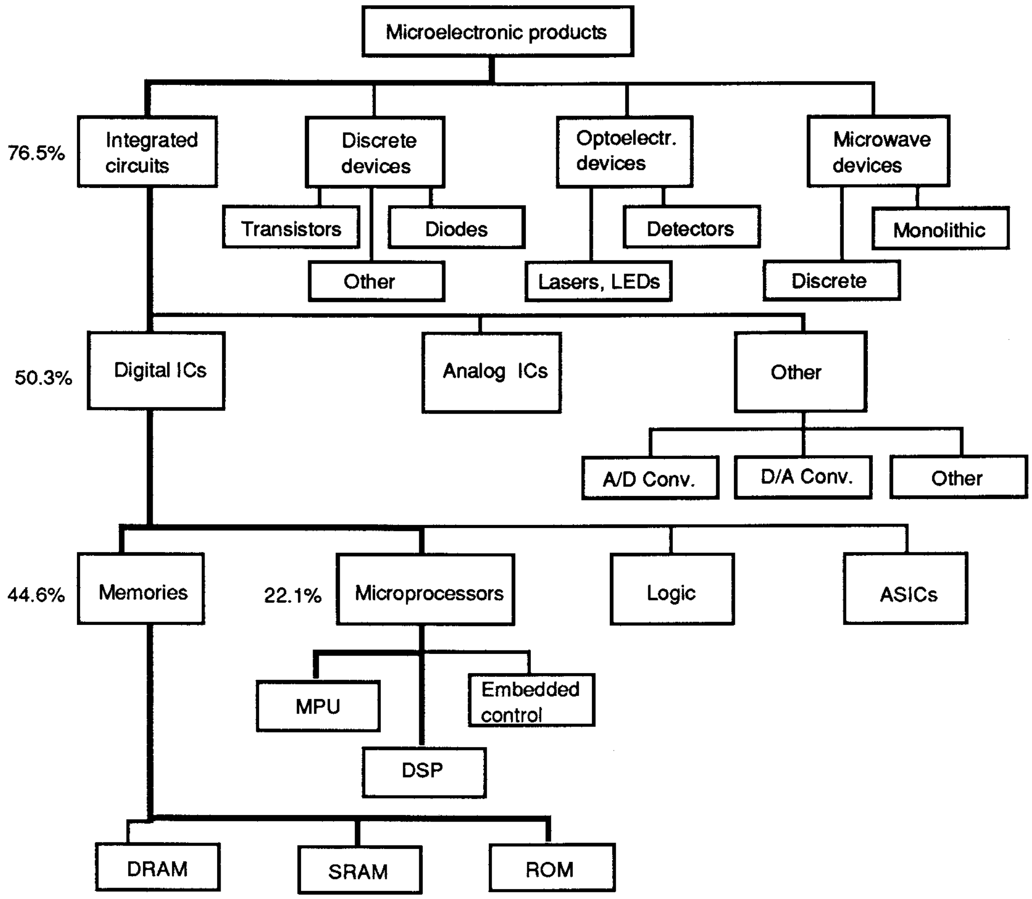
[31]WSTS Inc., *World Shipments and Bookings by U.S., European and Japanese Based Semiconductor Manufacturers*, administered by WSTS Inc., compiled by Price Waterhouse and Tohmatsu Awoki & Co., data for 1985 and 1986.

[32]*Defense Electronics*, September 1983, p. 69.

[33]Percentages shown in the figure are percent sales for the given product classification in 1987. These figures are based on data from WSTS Inc. and the Integrated Circuit Engineering Corporation.



SOURCE: Office of Technology Assessment, *Microelectronics Research & Development: Background Paper*, p. 28, with modifications.

Fig. 3--Classification of microelectronic products

Read-only memories (ROMs) permit the user to conduct only read operations, and, unlike DRAMs and SRAMs, preserve data even after power is turned off. Several classes of ROMs are alterable by the user, but not as easily or as many times as either SRAMs or DRAMs. Non-volatility is required in military applications when loss of stored data is unacceptable to the mission, memory power is subject to periodic and accidental interruption, and memory re-load is not viable due to time-criticality or data availability. In aircraft, ROMs can be found in cockpit data recorders, flight recorders, and missile

memories.[34] User-programmable ROMs are important in cases where information must be modified in the field.

In steps 2 and 3 of the methodology, each group of devices is assessed separately. A database is built for each group of products, and the ICs within the database are described in accordance with the structure of the model. Devices within each group are evaluated on the following characteristics:

1. circuit density
2. access speed
3. feature size
4. circuit power dissipation
5. time of introduction in the market
6. price[35]

The characteristics of interest are those at the time of introduction of the product, defined as start of general sampling. This point in time is chosen because learning curves and differences in capital investment by various firms do not have as much impact as they do at later points in the product life cycle.

In addition to the characteristics listed above, operating temperature range and radiation tolerance also distinguish commercial from military products. However, these are not characteristics that can be analyzed in the same way. The military temperature range has not changed over the past decade, and all circuits which are purchased by the military must be able to operate within this temperature range.[36]

Radiation tolerance information is not available for commercial circuits in other than a general way. An example of such general measurement is shown in Table 2.3. Individual commercial circuits are usually not tested for radiation tolerance, but different fabrication technologies have been evaluated and some of that information is incorporated in the analysis. Being designed for radiation tolerance is significant for some groups of components, less significant for others, as will be demonstrated by the multivariate regression analysis.

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[34]Roman Fedorak, "Information Storage and Retrieval Overview," Copy of Preliminary Charts, Advisory Group on Electron Devices, Special Technology Area Review on Nonvolatile Memory Technologies, June 23, 1988.

[35]Different measures of price are appropriate for different types of devices. \$/bit is appropriate for memories, \$/MIPS for microprocessors, etc.

[36]Questions have been raised, by the DSB among others, about whether it is sensible to require all military ICs to operate within such a wide temperature range. The specification is in effect at present, however, and every military circuit meets the specification unless special dispensation has been obtained.

The main source of data for this study is open literature. Information about products sold by merchant firms is relatively easy to obtain: in order to sell ICs, firms publish data sheets describing these ICs in detail. Prices and product characteristics are advertised in industry publications and described at conferences.

Table 2.3

RADIATION HARDNESS OF VARIOUS IC TECHNOLOGIES

	Technology		
	NMOS	Bulk CMOS	CMOS-SOS
Neutron hardness (n/cm^2) capability	$>10^{15}$-10^{16}	$>10^{15}$-10^{16}	$>10^{15}$-10^{16}
Total dose (γ) hardness capability (rads)	1-5 x 10^6	10^5-10^6	10^5-10^6
Dose rate (γ) or photo-current hardness capability (rads/s)	0.1-5 x 10^9	0.5-2 x 10^9	0.2-1 x 10^{11}

SOURCE: "Summary of IC Properties," Aerospace Corp., quoted in *Electronic Design*, January 8, 1981, p. 90.

Firms themselves are not the only sources of information. Because of its importance to the U.S. economy, the microelectronics industry is watched by a number of market research groups (including Dataquest, McGraw-Hill, Integrated Circuit Engineering Corporation, and In-Stat), investment houses and industry publications. These provide not only information on products, but assessments of technology, discussions of industry trends, and interviews with industry leaders. Many industry watchers are interested not only in the current products but in future products, and track research activities, conferences and scientific publications. Getting information on commercial research in progress is difficult because firms protect that information as competition-sensitive. It is discussed, in general terms, in trade publications and is easier to get for past years than for the present.

Information on products built by captive producers is more difficult to obtain. These firms generally keep the details of their component operations secret because of the competitive advantage provided by secrecy. Primary data for components produced by these firms are limited and are not as detailed as the information available from the merchants at the component level. Researchers employed by captives present papers at international conferences such as the annual International Solid State Circuits Conference (ISSCC), and their presentations are used as a way of approximating the devices which the captives intend to introduce in the future. Secondary data are available because

systems firms tend to be large, publicly traded, and their products are closely watched by market researchers and investment houses.

Unclassified government documents are available with descriptions of military ICs and research projects.

In order to place the firms within the model and allow correlation between firm characteristics and component attributes, information is required about the way the firms operate. This information includes the firm's history in the industry and information about its primary emphasis. Most of the data come from industry associations, histories of the industry, industry analyses, business school case studies, and histories of firms. Much of the "soft" data are gathered from interviews with R&D decisionmakers within the firms themselves, and those who watch the industry.

Table 2.4 presents overall counts of data points within the different categories in the database. Several comments should be made about the data. Both U.S.-based and non-U.S.-based firms are included. The database does not contain equal numbers of points in every category. For example, there are always many more points representing commercial ICs than points representing military ICs. This is due to two factors. First, the commercial market is much larger and more varied than the military market, so many more different ICs within each category can be expected to be sold in commercial markets. Second, information about commercial ICs is more readily available in open literature than information about military ICs. Availability of information is also the reason for the greater number of observations for component-oriented suppliers as opposed to systems-oriented firms. As discussed above, systems firms tend to be secretive about their component-level operations, and, if a component is not key to the sale of the system, it is generally not publicized.

Scarcity of information is most severe in the case of firms using the technology follower strategy. There is usually less publicity about the introduction of products by these firms, because, being available already, they are no longer "news." Given this and the rapid technological change within the industry, historical information about the capabilities and prices of these products at the time they were first introduced into the market is difficult to obtain. This difficulty is reflected in the database and, consequently, in the extent to which Hypothesis 4 can be tested.

Table 2.4

DATABASE CHARACTERISTICS--POINT COUNTS BY CATEGORY

	Microprocessors[a]	DSPs	SRAMs	ROMs
Total point count	79	67	106	126
Commercial	58	54	78	106
Military	21	13	28	20
Systems	20	20	6	15
Components	59	47	100	111
Leader	52	63	98	123
Follower	27	4	8	3

a. In the microprocessor product group, the counts presented in the Leader and Follower categories are those for Architecture Leader and Architecture Follower. This will be defined and explained in Section IV.

In most cases the difference in the number of observations in different categories does not present a problem, as there are sufficient observations of each kind to permit meaningful analysis. In cases where the number of points in a given category is so small as to make analysis meaningless, some illustrative charts are presented, and no attempt is made to draw conclusions about the support for the hypothesis in question.

Table 2.4 shows the number of observations in the database for each product group. However, data are not necessarily complete within each observation, i.e., not every characteristic of interest is available for every IC in the database. This means that not all product characteristics can be examined to the same extent. In order to have sufficient data for regression analysis, some of the missing data within observations were filled in by the following method. A regression was performed in which the IC characteristic of interest was used as the dependent variable, and Month of Introduction the independent variable. The resulting regression equation was then used to fill in missing data points within the characteristic of interest. Whenever the "filled-in" data series were used in integrative regression, this is noted in the description of the results.

Analysis Strategy

The analysis of each product group is presented in a separate section. The first three hypotheses are analyzed in a similar manner. For each product group, a cut is taken through the industry at one of the boundaries shown in Figure 1. A timeline of

development is then charted for each characteristic of interest. For instance, within the SRAM product group, development of access times is charted for commercial vs. military SRAMs, SRAMs produced by systems- and component-oriented firms, and SRAMs produced by technology leaders and followers. This provides a view of development of individual IC characteristics within the theoretical framework introduced in this section.

After individual characteristics are examined, a multivariate regression analysis is performed to determine whether different types of firms perform different trade-offs between product characteristics. After all, it is possible that if firms in military markets have different priorities than firms in commercial markets, for instance, they sacrifice performance along some dimensions in order to gain advantage along some other dimension. Month of introduction of a product is the dependent variable; technical and price characteristics listed above are independent variables. Dummy variables are included to differentiate military ICs from commercial, systems from component orientation, leaders from followers. The sign and significance of these dummy variables are of particular interest. Interviews with industry and government R&D managers are used for interpreting analysis results and examining the factors which played a role in the timing of product development and introduction, as well as the role played by commercial and military R&D funding in the development of advanced capabilities. A different regression model is fitted to the data for each component in order to reflect different relationships among variables for each product group.

Analysis of Hypothesis 2, dealing with the value of skipping generations through R&D projects, is somewhat different. The validity of attempting to skip generations through R&D becomes clear when the timing of product introductions is examined. A new generation of products appears as a quantum jump along some product characteristic or a group of product characteristics. Timelines of IC development are examined to determine whether such quantum leaps have taken place either in the military or commercial markets.

The final phase of the analysis involves a re-evaluation of the government investment strategy in semiconductors in view of the results of hypotheses analyses.

III. THE GOVERNMENT'S ROLE IN MICROELECTRONICS R&D

Before proceeding to an analysis of the hypotheses, let us examine the role that the federal government has played in the development of the microelectronics industry. It is important to understand this role because the government's R&D investment strategy grew out of the history of its participation in the industry and still reflects some of the ideas and patterns which were formed early on. This brief re-telling of the history of the microelectronics industry is focused on the methods and outcomes of federal government intervention, and especially on the government's use of R&D investment as a policy tool.

The history of microelectronics really began before World War II. As early as 1938 or 1939 Mervin Kelly, the research director at Bell Laboratories, knew that switching in telephone exchanges would eventually have to be done not by mechanical relays but by electronic connections if the growing volume of traffic was to be accommodated.[1] During those early days, however, such devices were only a theoretical possibility. In fact, the first solid-state amplifier built by William Shockley of Bell Labs in 1939 failed to work.[2] Electronic equipment using vacuum tubes came into use before World War II, and greatly grew in use and sophistication during the war. Widespread use of vacuum tubes, which were bulky and expensive, as well as notoriously fragile and unreliable, accentuated the need for research into alternative technologies, such as solid-state electronics. That was also the time when a strong link was forged between the military and the young microelectronics industry.

A HISTORICAL PERSPECTIVE ON MILITARY FUNDING OF R&D

Discrete Devices

The major breakthrough in solid-state electronics came with the invention of the point-contact transistor at Bell Labs in 1947. The development was a team effort by William Shockley, John Bardeen, and Walter H. Brattain, who shared the 1956 Nobel Prize in physics for their invention. Their research was part of a larger Bell Labs research program aimed at finding new and more efficient switching devices and amplifiers for telephone communications systems.[3]

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[1]Levin, op. cit., p. 40.

[2]Ibid.

[3]According to several sources, there is no evidence that latent military demand played a significant role in inducing the invention of the transistor. The Bell System was a large enough

By 1952, junction transistors were commercially produced by Western Electric, the manufacturing arm of AT&T. However, these early devices were not very reliable, operated within a restricted range of temperatures and electrical frequencies, and were difficult to produce. In addition, they were made of germanium, a relatively rare and, therefore, expensive material. In the early 1950s, solid-state electronics R&D efforts were concentrated in three areas: search for materials of greater purity in order to increase device reliability; development of devices that were capable of operating under a wider range of conditions; and search for semiconductor materials other than germanium. All of these goals were accomplished during the first decade. By 1954, Texas Instruments (TI) became the first producer of a silicon transistor, and enjoyed a three-year monopoly on the device. By 1956, TI became the innovator in production of high-purity silicon for use by the entire industry.[4]

Replacement of germanium by silicon as the main microelectronics material was gradual and driven mainly by military demand for products capable of operating within a wider temperature range than germanium made possible. With the invention of the integrated circuit, silicon demonstrated its advantage in formation of oxide layers and deposition of metallic films, which made its use advantageous for these devices. Production of silicon devices finally overtook production of germanium devices in 1966.

The first significant R&D effort at miniaturization of solid state devices was made by the Navy in cooperation with the National Bureau of Standards on a project called Tinkertoy. The objectives of the project were to reduce the size of electronic circuits and to automate the process of circuit assembly. The project spent about $5 million between 1950 and 1953 (approximately $26 million in 1982 dollars).[5] It was a technical success, but was made obsolete by the time it was over by concurrently developed transistor production methods.[6]

The crowning achievement of the discrete device era, and the bridge to the era of integrated circuits, was the invention of the Planar Process at Fairchild Semiconductor in 1958. This process technology, while originally used for mass production of transistors, was ideally suited for the production of integrated circuits.

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customer to justify significant expenditures of R&D funds. (See, for example, Levin, op. cit., p. 58.)

[4]Levin, op. cit., p. 43.

[5]The deflators used in this paper are deflators for total federal government purchases of goods and services taken from the table of implicit price deflators for gross national product, 1929-87, in the Economic Report of the President, 1988, p. 253.

[6]Levin, op. cit., p. 70.

Integrated Circuits

G.W.A. Dummer of the Royal Radar Establishment in Great Britain is credited with the idea that led to integrated circuits. He wrote in 1952:

> With the advent of the transistor and the work in semiconductors generally, it seems now possible to envisage electronics equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials being connected directly by cutting out areas of the various layers.[7]

Dummer's proposal intrigued scientists worldwide, and the race for the invention of the integrated circuit was on.

Throughout the 1950s the U.S. military showed an intense interest in miniaturization of electronic devices. Several different approaches were tried. The Army Signal Corps spent $26 million (approximately $105 million in 1982 dollars) between 1957 and 1963 on the Micromodule Program, mainly at RCA. The Army's Diamond Ordnance Fuze Laboratories funded a program of in-house and contract research in "thin-film" circuits between 1957 and 1959. The Navy began its own "thin-film" circuit program in 1958. In the meantime, the Air Force pursued "molecular electronics"--development of solid-state devices that performed the function of electronic devices but did not correspond part for part to conventional circuits. The integrated circuit, as it later became known, did not fit into any of these programs.[8]

Jack S. Kilby of Texas Instruments, working without government funding but aware of government interest, demonstrated the first working circuit composed entirely of semiconductor elements on August 28, 1958. Although his was not a wholly integrated circuit, it was a significant advance in the state of the art. Kilby's next step was to lay out all the components on a single bar of germanium, and this circuit was demonstrated on September 12, 1958. He took steps to patent the device in January 1959; the device was revealed to the public on March 6, 1959. After the demonstration of Kilby's device, Texas Instruments began dropping its other microminiature products and concentrated on moving the integrated circuit from the laboratory to the marketplace.[9] The support from the military proved critical at this stage. Although the Air Force did not abandon its

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[7]Quoted in F. X. Ross, *The Magic Chip*, J. Messner, New York, 1984, p. 17.
[8]Levin, op. cit., pp. 70-72.
[9]Ross, op. cit., p. 21.

molecular electronics program, it did award a $1.15 million contract to TI to design and fabricate circuits that would perform specific functions and would be made of silicon.[10]

While Kilby's devices were fabricated by hand in the laboratory, Robert Noyce at Fairchild realized that the Planar process could translate the laboratory curiosity into a commercially viable product. Noyce filed a patent application for a planar integrated circuit in July 1959, and a lengthy patent dispute followed. Eventually, the dispute was resolved in favor of Noyce. The main driving force in further development of integrated circuits was miniaturization.

The advantages of miniaturization were most important to the military and the manufacturers of computers. While discrete components were quite reliable by 1960, the large numbers of components within systems introduced unacceptably high failure rates. In addition, many failures occurred in the interconnections between components. Integrated circuits had the potential to solve both problems.

Initially, however, integrated circuits were greeted with skepticism in the private sector. In fact, IBM, which in 1960 was the largest single private-sector customer of every major semiconductor house, opted against the use of integrated circuits in its new 360 series of computers.[11] Two government procurement decisions were responsible for moving integrated circuits into large-scale production. In 1962 NASA announced that its prototype Apollo guidance computer would use integrated circuits. Shortly thereafter, the Air Force announced the use of integrated circuits in the Minuteman II guidance package. Although considerable risk was involved in these choices of a relatively new technology, both agencies decided to opt for the high-risk high-return alternative.

In addition to providing the solution to technical problems, miniaturization was thought capable of lowering the cost of chips. Since most of the cost of fabrication occurred in wafer processing and in subsequent assembly and packaging operations, it was conjectured that increasing the number of components on a single chip would not raise the cost of the chip proportionately. This proved to be true. The progress of miniaturization moved from Medium Scale Integration in the 1960s, to Large Scale Integration in the 1970s, to the Very Large Scale Integration of today. Before the end of the century, we might see Ultra Large Scale Integration, involving as many as a billion components on a single chip.[12]

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[10]Levin, op. cit., p. 72.

[11]Levin, op. cit., p. 62.

[12]John W. Wilson, et al., "Superchips: The New Frontier," *Business Week*, June 10, 1985, p. 83. Integration levels are defined in Appendix A.

As semiconductor technology developed, greater resources have been necessary to advance the state of the art. R&D spending as percentage of sales by the merchant semiconductor sector over the past 15 years is shown in Figure 4.[13] Since the industry is now at approximately $20 billion per year, 10 percent of sales spent on R&D is approximately $2 billion. The two sharp increases of R&D expenditures as percentage of sales have the following plausible explanations. In 1980, the DoD started its VHSIC Program. In order not to fall behind the firms which were participating in the VHSIC Program, other merchant semiconductor manufacturers sharply increased their R&D investment. In addition, Japanese competition was beginning to be felt at that time, and U.S. firms tried to maintain absolute R&D funding levels despite the slump of 1981-82 in order not to fall behind the Japanese. As sales fell, the constant dollar level of R&D spending came to comprise an increased percentage of sales.[14] The increase in R&D which took place in the mid-1980s was probably a reflection of another slump in the semiconductor markets which took place around that time.

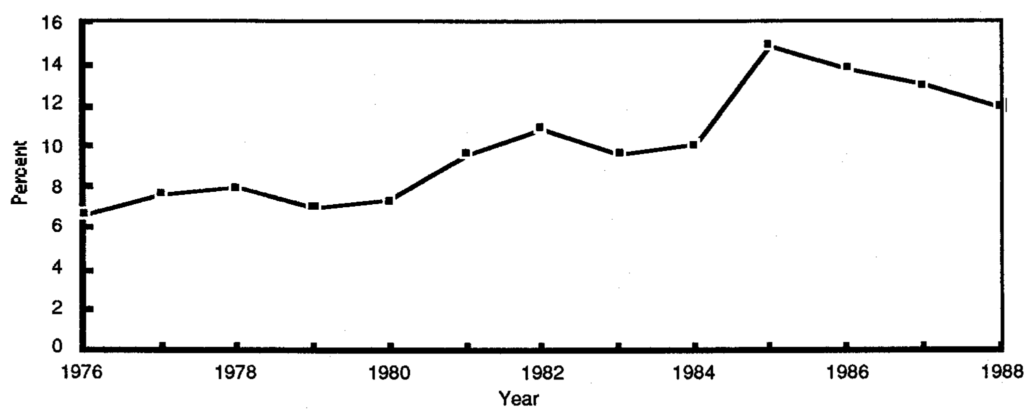

Fig. 4--R&D as percentage of sales (merchant sector)

Comprehensive figures for government expenditures on semiconductor R&D are not available because many agencies are involved and because these R&D expenditures are seldom identified as such. A Congressional Budget Office study found that the total

[13]Data provided by the Semiconductor Industry Association. These data do not include R&D spending by captive semiconductor manufacturers, which are not available. By some estimates, U.S. captive suppliers account for 30% of worldwide semiconductor production.

[14]W.F. Finan and A.M. LaMond, *Sustaining U.S. Competitiveness in Microelectronics*, Harvard Business School case study, pp. 167-168.

federal outlays for semiconductor R&D in fiscal year 1987 were approximately $450 million (about $340 million of it provided by the DoD, and $60 million provided by the Department of Energy, mostly for work at national laboratories).[15] As a point of comparison, approximately $1.7 billion were spent by the merchant semiconductor industry during the same time period. As discussed in Section II, much of the DoD funding goes to systems-oriented firms which are generally not included among merchant semiconductor producers.

As microelectronic devices came to be used in more and more sectors of the economy, the size of the market increased enormously. While the military's use of integrated circuits also grew, its share of the integrated circuit market fell sharply by the mid-1970s, as shown in Figure 5.[16] So did the enthusiasm of commercial firms for participating in military markets.

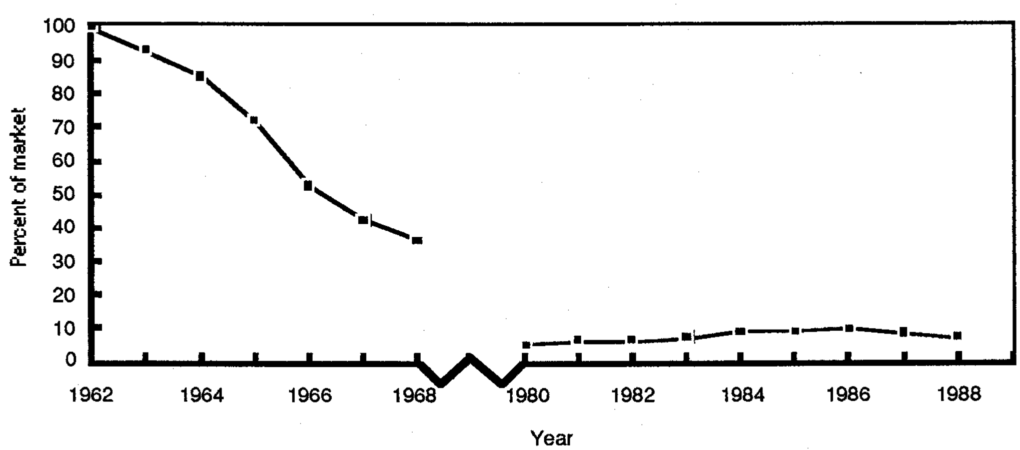

Fig. 5--Government share of integrated circuits

As a result, the military has found it increasingly difficult to stay on the leading edge of technology. This led the Department of Defense to start a high-priority R&D program in 1979 to develop Very High Speed Integrated Circuits (VHSIC) for military applications. The goal of the first phase of the program was to create a fivefold improvement over the best ICs available in the laboratory at that time. The second phase

[15]Congress of the United States, Congressional Budget Office, *The Benefits and Risks of Federal Funding for Sematech*, September 1987, p. 60.

[16]Data for 1962 to mid-1970s from Levin, op. cit., p. 60. Data for the 1980s from Integrated Circuit Engineering Corp.

involved a 20-fold improvement over Phase 1.[17] Program cost started out at approximately $200 million, and approached $1 billion by the time the program ended in 1989.

While the VHSIC Program was not aimed at commercial markets, there is a possibility that techniques developed in the program will be taken over by the participating commercial firms into their VLSI programs. The commercial potential of VHSIC technology is most clearly demonstrated by the fact that companies that did not choose to participate in the DoD program, or those that were dropped during the down-selections at various stages, have been actively pursuing their own VLSI programs, often along the lines similar to VHSIC but on more relaxed schedules.[18] The VHSIC Program and its potential in the commercial marketplace will be discussed in greater detail below. An interesting development is the qualification under VHSIC standards of VLSI chips not developed under the VHSIC Program. Both Intel, which never participated, and TI, which was dropped after Phase 1, have successfully sold such chips to the military.[19]

The VHSIC Program

By the late 1970s, many of the larger defense systems suppliers were frustrated with their inability to get advanced ICs for military systems. The VHSIC Program, started in 1979, was by far the single largest R&D effort directed at the microelectronics industry. At the start of the program, the Pentagon told potential VHSIC bidders that it preferred to award contracts to defense electronic system suppliers, rather than to IC producers.[20] The logic behind this was that systems suppliers would be more likely to use the new chips in military systems. However, systems houses were encouraged to team up with commercial semiconductor suppliers in order to assure that the outputs of the Program would be widely disseminated within the defense supplier community.

In 1980 the DoD selected nine contractors for Phase 0, a group of nine-month program definition studies. Five of the nine winners were teams of military system and semiconductor firms: General Electric, teamed with Intersil; Hughes Aircraft, teamed with Signetics; Raytheon, teamed with Fairchild Semiconductor; TRW, teamed with Motorola; and Westinghouse, teamed with National Semiconductor. The remaining

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[17]Ken Julian, "Defense Program Pushes Microchip Frontiers," *High Technology*, May 1985, p. 49.

[18]Julian, op. cit., p. 57.

[19]Tobias Naegele, "Ten Years and $1 Billion Later, What Did We Get from VHSIC?" *Electronics*, June 1989, p. 98.

[20]See, for example, Levin, op. cit., p. 92.

contractors were companies whose products included both military and commercial systems: Honeywell, Rockwell International, Texas Instruments and IBM. Phase 0 winners submitted their proposals for Phase 1 chip design and fabrication, and the field was narrowed to six Phase 1 contractors: Honeywell, Hughes, IBM, Texas Instruments, TRW and Westinghouse.

The six Phase 1 contractors were given complete freedom to select the technologies they preferred to use, although some general goals were specified. In order to meet VHSIC standards, ICs had to be designed with line widths of 1.25 μm, have a functional throughput rate of at least 5×10^{11} gate-Hz/cm^2, include on-chip test features that cover 95 percent of a chip's logic gates, operate at a minimum clock speed of 25 MHz, and meet basic reliability, radiation tolerance, and temperature specifications. As a result, a wide range of technologies was investigated. ICs to be fabricated during the program, proposed by the contractors, also differed widely. IBM was the most conservative, proposing to produce a single chip; the TRW/Motorola team designed a family of 13 chips. Only IBM, with its relatively modest objectives, was able to meet the original Phase 1 schedule; other contractors were some months behind schedule, but all delivered working ICs. Beyond having significantly higher processing power, most Phase 1 chips incorporated other novel features, such as self-test functions and redundant processors that would be engaged in case of malfunction.

Each contractor or team was given general figures of merit for its circuits, but was encouraged to pursue its own approach and technology to achieving these figures. The DoD encouraged information sharing among teams. A central repository was created in which all VHSIC reports were stored and access was permitted to all who qualified. An industry standard was established for the documentation of the VHSIC process and products.

> [Information sharing] was done via semiannual meetings at which each contractor reported its accomplishments and its current problems. Additionally, if one contractor encountered a particularly sticky problem--say, in dry-etching metal interconnections--and a survey of others revealed similar difficulties, a special meeting was convened so each could describe the solutions it was exploring.[21]

In addition to its concern with improving IC performance, the DoD was also concerned with the cost of ICs. The microelectronics industry is characterized by steep learning curves. The costs of early ICs are high because yields are typically low. In order to reduce the cost of VHSIC ICs as quickly as possible, the DoD awarded a $15

[21] Julian, op. cit., p. 52.

million yield-enhancement contract to each of the Phase 1 contractors. The 32-month contracts were designed to allow each contractor to improve its own specialized fabrication process so that the yield of good chips could be increased to about 10 percent, typical of VLSI yields. In addition to these funds, the three services spent about $100 million as part of their manufacturing technology improvement effort on process technologies that could be used by all VHSIC contractors.

Phase 2 was launched in 1984 and called for development by 1988 of new chips with minimum features of 0.5 μm, compared to the 1.25-μm features of the Phase 1 chips. The bidders included the six Phase 1 contractors and AT&T Technologies, teamed with Raytheon and E-Systems. As part of its concern with moving VHSIC technology into the field, the military required each Phase 1 contractor to provide the government with a VHSIC demonstration module (a brassboard system or subsystem) prior to selection of Phase 2 contractors. Phase 2, the final phase of the program, included three contractors: IBM, Honeywell, and the TRW/Motorola team. (Motorola also did some work for Honeywell.) Each contractor received $60 million for a three-year effort. Phase 2 winners continued to develop the wide range of technologies they began developing in Phase 1. IBM's Federal Systems Division announced in May 1988 that it successfully produced the first functional chip developed under Phase 2. IBM had once again chosen the most conservative approach, and succeeded before other program participants. Not all features on its chips were reduced to 0.5 μm, although that is the minimum feature size. On the other hand, TRW had chosen a more sophisticated technological approach, which included scaling of all dimensions to 0.5 μm, the development of wafer-scale integration theory, and the capability to reconfigure the chips in operation should a malfunction occur. The TRW/Motorola team delivered its chip, the CPUAX, in April of 1990. Although it did not have quite all the capabilities originally envisioned for it, the chip is the largest integrated circuit ever produced (almost 2" on the side) and includes nearly 4 million transistors.

As part of the transition into sub-micron technology, the DoD spent about $60 million on Phase 3, research and development of design and fabrication techniques for Phase 2. (Phase 3 chronologically precedes Phase 2.) About 50 Phase 3 contracts were awarded in 1980-81.

The contractors and the government were concerned that those companies that remained in the VHSIC Program following various selections would gain a significant competitive advantage over others in the marketplace. In order to remedy the situation, the DoD sponsored a series of three-day workshops in major cities around the nation for

nonparticipants. Nonparticipants were also encouraged to obtain CAD tools developed by VHSIC prime contractors to allow other companies to develop their own custom-designed chips.

In order to meet the objective of improving weapons systems through the use of advanced electronics, the DoD has placed emphasis on getting VHSIC technology from the laboratory into the field. E.D. Maynard, the VHSIC program director, initiated a "technology insertion" program that would retrofit existing military systems with new plug-in cards, using Phase 1 chips. So many potential applications were found that the services used their own funding for studying these applications in addition to using funds available from the VHSIC Program office. The insertion program was also envisioned as a means of diffusing VHSIC technology throughout the defense contractor community: nearly half the winners of technology insertion contracts did not participate in the Phase 1 program. Despite this, however, the movement of Phase 1 chips into the field has been slow and disappointing to the industry. VHSIC contractors blamed the reluctance of weapons program managers to risk the use of untried technology, exacerbated by the fact that the new chips are still expensive compared to the older ICs on the market. These chips are being designed into new weapons systems, however.

It is still difficult to assess whether the VHSIC Program will have a significant effect on commercial markets. A number of commercial IC manufacturers did not wish to participate in the program because they did not want to deal with the limitations imposed by the specialization of VHSIC chips, and by possible security restrictions. The DoD imposed restrictions on use of VHSIC technology because it was afraid that premature commercialization would allow the Soviets to duplicate the advances made in the Program. Rules were set up to restrict not only the ICs themselves, but also process innovations associated with them. Now contractors that participated in the program are unhappy with the restrictions. They are concerned that the Japanese will gain a major competitive advantage while the best U.S. technology is restricted to military applications. In addition, the contractors have invested about $300 million of their own money as well as some of their best design engineers and managers into the development of VHSIC chips, probably in the expectation that they would be able to reap the benefits available beyond the military markets.[22] Some manufacturers feel that large volumes available in commercial markets are necessary to make prices sufficiently low to induce

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[22]Brueckner and Borrus estimate the contractor contribution at as much as three times contract value. [L. Brueckner and M. Borrus, *Assessing the Commercial Impact of the VHSIC (Very High Speed Integrated Circuit) Program*, December 1984, pp. 72 ff.]

wide-spread application of VHSIC-type technology. Honeywell has offered its VHSIC facility for sale.

At this point, the interests of the contractors and the interests of the DoD are in conflict: while the DoD wants to restrict commercial applications and to disseminate the technology within the defense contractor base, the program participants want to use VHSIC technology in commercial applications and to restrict their rivals' access to the technology. Whatever the restrictions, it is expected that VHSIC-type chips will find their way into the commercial systems produced by program participants. In the meantime, some firms which participate in both commercial and military markets have created two parallel research efforts (supported with massive documentation) in order to avoid military restrictions on their commercial VLSI products.[23]

Although the VHSIC Program itself did not contribute more than 10 percent of industry R&D funding in any given year, it helped focus the industry's attention on VLSI development. Firms which participated in the Program made significant contributions of their own funds in order to meet the demanding technical requirements. The companies that did not participate in the VHSIC Program or those that were dropped during the various phases have been funding their own programs to produce chips with performance characteristics similar to those VHSIC chips. In 1982 General Electric funded its own Advanced Very Large Scale Integrated Circuit (A/VLSI) program which was running about a year behind the VHSIC program schedule. Raytheon has funded its own program as well. Intel, which refused to participate in the VHSIC Program from the beginning, unveiled its new microprocessor, the 80486, in late 1989. This chip includes over 1 million transistors and uses 1-μm technology. Intel's M51C98 radiation-resistant 64-kilobit static random access memory chip has been qualified as a VHSIC Phase 1 device, as has its 32-bit 80386 microprocessor. Texas Instruments has adapted its Epic II commercial 0.8-μm CMOS process for military products, and is slated to produce the chip set for the mission control computer in the Advanced Tactical Fighter.[24]

All this is a good indication that the chips produced under the VHSIC Program are a logical step in the development of microcircuits, rather than a specialized product that will be of use only to the military.

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[23]Ibid.

[24]Tobias Naegele, "Ten Years and $1 Billion Later, What Did We Get From VHSIC?" *Electronics*, June 1989, p. 99.

Other DoD R&D Funding

Although by far the largest, the VHSIC Program has not been the only DoD source of funds for microelectronics R&D. The Defense Advanced Research Projects Agency (DARPA) supports long-term research for military applications, including research in microelectronics.[25] The two major areas of emphasis are materials and devices research, and architecture design and manufacturing. Since its mission is to sponsor R&D with a long time horizon, DARPA's materials and devices R&D funding is concentrated on compounds other than silicon, such as gallium arsenide.

DARPA's funding of architecture designs was important historically to the development of microprocessors. DARPA's funding at Stanford University and University of California Berkeley led to the development of Reduced Instruction Set Computing (RISC) architectures. RISC and DARPA's role in its development will be discussed in Section IV, Microprocessors. In addition, the Agency spends funds on exploratory development in automation and fast-turn-around fabrication of ICs. DARPA also serves as the channel for the government's $100 million per year contribution to the Sematech Consortium.

R&D AND PROCUREMENT AS INSTRUMENTS OF POLICY

Richard C. Levin describes the impact of public policy on the semiconductor industry as follows:

> In comparison with sectors such as agriculture and aviation, the contribution of public policy in microelectronics has been modest, but nevertheless of considerable significance. Without question, the most important policy instruments influencing technical advance have been the public procurement of electronic components and systems--principally by the military services--and public support for research, development, and production engineering--principally by the military and NASA, with some contribution from the National Science Foundation and the National Bureau of Standards.[26]

Although a wide range of government policies can be examined in connection with the microelectronics industry, in this section I will examine only two: government procurement of microelectronics and government support of R&D. Others, such as the effects of security regulations, patents, and taxation, have been examined in Levin's case study.

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[25]CBO, op. cit., pp. 61 ff.
[26]Levin, op. cit., pp. 9-10.

Government Procurement

While the transistor was not invented with the military in mind, the introduction of silicon and the development of integrated circuits were clearly driven by the size of latent military demand. The military was prepared to pay a high price for reliable devices to replace vacuum tubes: a 1952 study showed that 60 percent of the Navy's electronic equipment was not operating satisfactorily because of tube problems; the Air Force was concerned not only with the reliability, but size and weight of components as well. Military requirements were clear and specific: weight savings, lower power consumption, operations under adverse conditions such as high temperatures and high levels of radiation, and low failure rates. The military was ready to be the first buyer of new products and to pay premium prices for them. The military also demanded highest quality products. As a result,

> [d]ata reported to the Defense and Business Services Administration of the Department of Commerce (1960) indicate that the average unit price for devices sold to the military was roughly twice that received from private sector customers in middle and late 1950s.[27]

The Army's Signal Corps led service units in the purchase of semiconductors in early and mid-1950s. These devices were incorporated into communications equipment, such as radios. In 1958, when the Air Force decided to rely on semiconductors for its Minuteman missile program, demand jumped. The military supported several suppliers, at least in part because no single supplier could make deliveries at the required rate.

Texas Instruments made a conscious effort to become the first company to make a silicon transistor available to the military, and did so in 1952, as was discussed above. This breakthrough led TI to become the largest merchant supplier of semiconductor devices.[28] Once semiconductors were well established, it became clear that there would be a great prize available to those who could create an integrated circuit device. Each service branch established its own R&D program to further miniaturization of electronics, and each program took a completely different approach. In fact, the successful approaches that emerged from TI and Fairchild were different from those funded by the government, but the diversity of programs served as a clear indicator that the military was interested in the result. Apparently, TI had the military exclusively in mind when Kilby developed the integrated circuit.[29]

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[27]Levin, op. cit., p. 59.
[28]Levin, op. cit., p. 61.
[29]Levin, op. cit., p. 62.

Because of the skepticism with which integrated circuits were regarded early in the development cycle, the government was the exclusive purchaser of the devices through 1963 and most of 1964, as was illustrated in Figure 5. Several benefits resulted from NASA's Apollo decision and the Air Force's Minuteman II decision.[30]

- The willingness of the government agencies to pay high prices for initial units provided incentive for the producers to enter the field, justifying the initial investment.
- The large volume of orders facilitated learning and allowed costs to fall--very important in an industry with a steep learning curve.
- Government progress payments provided cash flow and reduced technical risk.
- The military provided a very high level of user feedback which facilitated learning.
- Technology was pushed by the exacting requirements of the Air Force.
- The government's policy of second-sourcing facilitated the transfer of know-how and technological capability between companies. Far from creating ill will between companies, second-sourcing was viewed as beneficial: new entrants with innovative products found advantages in second-sourcing their new products to larger established firms in order to ensure that they had customers for these products, or in acting as second sources in order to secure cash flow while they built markets for their new products.

In some cases, devices designed for the military were transferred directly into the civilian markets. In most cases, the spillover was indirect and took the form of suppliers building on their military production experience to create ICs for commercial applications.

It appears that in recent years the direction of technological spill-over in many defense-related technologies, including electronics, may have reversed.[31] This is not unreasonable, given the much larger size and diversity of the civilian electronics markets, as discussed above. The larger size of commercial markets presents commercial firms with a reason to develop advanced commercial technologies for these markets, and presents an opportunity for the military to take advantage of these developments, just as

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[30]The points below are taken from Levin, op. cit., pp. 63-65.

[31]Congress of the United States, Office of Technology Assessment, *The Defense Technology Base: Introduction & Overview*, February 1988, p. 29.

commercial markets benefited from military procurements in the early days of the industry.

Government Support for R&D

Although there was early support for semiconductor R&D by the military, NASA, the National Bureau of Standards and the National Science Foundation,

> [s]ubstantially none of the major innovations in semiconductors have been a *direct* result of defense sponsored projects. Major advances in semiconductor technology have with few exceptions been developed and patented by firms or individuals without government research findings *[sic]*. Far fewer patents have resulted from defense supported R&D than from commercially funded R&D, and a far smaller proportion of those which have resulted from defense support have had any commercial use.[32]

Once the inventions were made, however, the government (and the military in particular) realized their value and supported their practical realization. As soon as the government was informed of the initial Bell discoveries in July 1948, it moved to award Bell an R&D contract to expedite transistor development. As soon as batch processing of transistors and other discrete devices became possible, the Department of Defense moved to develop a large industrial manufacturing capacity in semiconductors. In 1956, the Signal Corps committed $14 million ($65 million 1982 dollars) to production refinement contracts in the transistor area. The government agreed to pay for all engineering design and development effort, while the twelve firms involved paid for capital equipment and plant space.[33]

The military's R&D programs during the time the integrated circuit was invented were described above. Although the integrated circuit was developed without government funds and did not fit into any of the programs funded by the military, the Air Force quickly realized that this was a natural transition to miniaturized electronics and provided contracts for further development.[34] The most striking feature of government participation in R&D and production engineering support during the 1950s and 1960s is the flexibility with which it responded to technical innovation. It encouraged technical risk and multiple approaches, and was ready to try new products and new firms. According to Levin, this readiness to take advantage of events stemmed from the fact that

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[32]Massachusetts Institute of Technology, *The Influence of Defense Procurement and Sponsorship of Research and Development on the Development of the Civilian Electronics Industry*, NBS-GCR ETIP 78-49, June 30, 1977, p. 2.

[33]Levin, op. cit., p. 67.

[34]Levin, op. cit., p. 72.

the government was a major potential user of the products. Its requirements were clearly specified and the role of new products was clearly envisioned.

It is in this light that one should examine the most recent government research program in the semiconductor area--the VHSIC Program. In some ways the VHSIC Program is remarkably similar to earlier government efforts: the chips that were developed were developed strictly with the military markets in mind, a multiplicity of approaches was encouraged, and data sharing among contractors was institutionalized. If the past is any indicator of the future, however, the major breakthroughs in technology will not come from the VHSIC Program, but from commercial manufacturers, working to meet demands of commercial markets.

In addition to its involvement in research for its own purposes, the government has also become involved in helping the U.S. semiconductor industry do research that would increase the industry's ability to compete in world markets. A research and development consortium, Sematech, has been set up in Austin, Texas as a cooperative venture between industry and government. The government contributes $100 million per year and the industry members contribute $150 million per year. The industry members include IBM, Intel, DEC, AT&T, Texas Instruments, Motorola, National Semiconductor, Harris Corporation, Rockwell International, NCR, LSI Logic Corporation, Micron Technology, Advanced Micro Devices, and Hewlett-Packard. The government contributes its funding through the Defense Advanced Research Projects Agency. Until his death in June 1990, Robert Noyce, the co-inventor of the integrated circuit and one of the most respected people in the industry, headed the consortium as chief executive officer. The consortium's objectives are to significantly improve yield at wafer probe, to advance submicron processing technology, to advance wafer fabrication manufacturing equipment, and to advance X-ray lithography processing capabilities. Over time, the consortium has focused on supporting the U.S. semiconductor manufacturing equipment industry, perceived as the weak link in the microelectronics production chain. While this venture is expected to benefit participating U.S. semiconductor manufacturers,[35] concerns about the products of the research have been expressed by both industry and government. Industry observers are worried that the government will try to direct the research because of the magnitude of its investment in the consortium. Government observers are worried

[35]Others, including foreign manufacturers, can buy the results of Sematech research after two years.

that the manufacturing processes and chip designs produced will not meet military specifications. It is too early to predict how these concerns will be resolved.

The government, especially the military, has clearly played an important role in the development of the U.S. microelectronics industry. The government's willingness to take risks on new technology and to promote its use were significant drivers in creating a strong industrial base in microelectronics. Government-sponsored research and development did not produce the major advances in the industry, but by allowing different approaches and technologies to be explored, the government was in effect allowing the industry to "hedge" its technological bets. It was believed that the more different approaches are tried, the greater the chances that one of these approaches will prove to be "the right one." The fact that the government was not the one to fund the relevant discovery is unimportant--increasing available resources for R&D and standing ready to buy the products resulting from it provided for the industry's growth.

Still, given the fact that the major advances were not made using government funding, it is tempting to believe that the microelectronics industry would have come to exist and flourish even without a massive infusion of government funding. At best, government intervention might have produced the industry a few years earlier than it would have happened without intervention. In fact, the military seems not to have adjusted to the fact that the commercial market became dominant in the 1970s and underestimated rapidity or nature of commercial developments.

The VHSIC Program is a good example of this proposition. The Program emphasizes miniaturization--the strategy pursued by commercial manufacturers without government funding. While the existence of the program may have prompted firms to speed up their quest for ever-denser chips, the development of VHSIC-type integrated circuits is a logical extension of current technology. VHSIC chips possess special features, such as a wider range of acceptable operating environments and self-test capabilities, which are more important in combat than in commercial applications. Nevertheless, the basic technology that makes them possible is technology that is being pursued without the motivation provided by military markets. One of the most highly touted features of VHSIC chips was the small feature sizes with which these chips are manufactured. However, 1-megabit DRAMs with approximately 1-μm feature sizes were introduced at the International Solid State Circuit Conference in February 1984, while VHSIC Phase 1 was still working on 1.25-μm features. CMOS manufacturable feature sizes dropped to 1 to 1.25 μm by 1985 in the commercial market. In fact, proponents of greater integration between the civilian and the military industrial sectors contend that the

ICs currently built for commercial applications (such as those hard-mounted on automobile engines) can already withstand the environments specified for military applications.[36]

The major benefit of the VHSIC Program may have been the increased concentration of U.S. chipmakers on long-term R&D. According to an International Resource Development study,

> private firms--particularly the smaller ones--tend to emphasize R&D that is most likely to bring short-run success. . . . In fact, many companies defer research projects until they are fairly certain that they have a high likelihood of success: one survey of industrial research found that three-fourths of the projects begun in private laboratories had success probabilities of 80% or more, while only two percent had success estimates of less than 50%. . . . Even worse, a large amount of private R&D by electronic firms consists of so-called "reverse engineering". . . [which] duplicates research that has already been performed and contributes nothing to scientific and technical knowledge.[37]

If the VHSIC Program corrects for this to some extent, it may be money well spent. The final evaluation of the effect of the program will have to be delayed until VLSI technology becomes more common, and the role of VHSIC in promoting this technology becomes more clear.

The relationship between the military and civilian microelectronics markets is more complex now than it was when the industry was in its infancy. While the military still requires high technology in specific areas, the approaches taken by the commercial industry result not only in lower-cost ICs, but in ICs which are more technologically advanced. The military perceives the source of its lag in microelectronics as one of getting chips from the laboratory into operating systems, which has resulted in a strategy of rapid insertion of chips into military systems. This was a prominent part of the VHSIC Program, both in the selection of systems contractors as primes and in the establishment of a separate insertion program within VHSIC.

The problem with these approaches to early insertion is that rapid chip development is often incompatible with optimal chip performance and low-cost production strategies.[38] Additionally, the VHSIC Program concentrated on improving the state of the art but did not take account of concurrent development in firms which were

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[36]Jacques S. Gansler, "Integrating Civilian and Military Industry," *Issues in Science and Technology*, Vol. V, No. 1, Fall 1988, p. 70.

[37]International Resources Development Inc., *VHSIC--Military and Commercial Opportunities*, Report No. 705, Norwalk, Connecticut, July 1986, p. 75.

[38]Brueckner and Borrus, op. cit., p. 51.

already advancing the state of the art for commercial markets. It is not surprising, therefore, that firms which did not participate in the VHSIC Program, and were seemingly behind the participants technologically, are having an easier time marketing their VLSI chips under VHSIC qualifications than the firms which took part in the program.[39] This study did not examine the length of time it takes to move an IC from demonstration into commercial or military products, however, but focused on whether the military's R&D strategy made the most advanced ICs available in military markets.

In order to try to resolve some of the issues tangled up with the government's role in the development of microelectronics during the recent years, let us now look at the development of four specific classes of products. We will look at the way these products developed, the characteristics of military and commercial products, and the role played in the development by military R&D.

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[39]Naegele, op. cit., p. 99.

IV. MICROPROCESSORS

This section presents the analysis of hypotheses advanced in Section II as they apply to microprocessors. A history of microprocessor development, concentrating on the period between 1980 and 1989, is presented in Appendix B. This history is important because the analysis hinges on understanding the timeline of microprocessor evolution. Familiarity with it will be assumed.

CLASSIFYING FIRMS

The first step in the analysis is the classification of firms in accordance with the taxonomy developed in Section II. The microprocessor data base includes information from open literature. Consequently, it includes a large number of firms, but the distribution of firms in various categories is uneven. The firms whose products are included in the data base are listed in Table 4.1, together with the classification within the taxonomy developed in Section II with a single exception. Although the nomenclature of Section II presents three categories into which firms can fall, microprocessors are a special case--there are two ways in which a firm can be classified as leader or follower. A firm can be leader or follower in architecture either by introducing original architecture or by manufacturing a processor with an architecture designed by another firm. A firm can also be either leader or follower in manufacturing technology. These will be treated separately. Let us now discuss classification of major firms in the microprocessor market.

The major players in the complex-instruction-set computing (CISC) market have been Intel and Motorola. Both of them are classified as component firms, as well as architecture and technology leaders. Both firms have been active in selling their microprocessors to systems suppliers, the main characteristic of component-oriented firms. Both firms have made forays into the systems market, but without great success in computers and workstations--the major users of general purpose microprocessors.

Both Intel and Motorola have been leaders throughout their history in the microprocessor market. The Intel and Motorola CISC architectures are designed to run with different operating systems and different sets of software. This is a clear expression of architecture leader strategy, as is the rivalry between the firms. Although the latest generation of CISC microprocessors, the 80486 and the 68040, includes similar components on chip, the basic difference in architectures remains.

Table 4.1

CLASSIFICATION OF MICROPROCESSOR PRODUCERS

Firm Name	Commercial or Military	Systems or Components	Architecture Leader or Follower	Technology Leader or Follower
AMD	C	Co	AF	TF,TL
AT&T	C	S	AL	TL
BIT	C	Co	AF	TL
Cypress	C	Co	AF	TL
DEC	C	S	AF	TL
Fairchild	C, M	Co	AF	TL
General Dynamics	M	S	AF	TL
Harris	M	Co	AF	TL
Hewlett-Packard	C	S	AL	TL
Hitachi	C	Co	AF	TF
Honeywell	C	S	AL	TL
IBM	C	S	AL	TL
Intel	C, M	Co	AL	TL
LSI Logic	M	Co	AF	TL
McDonnell Douglas	M	S	AF	TF
MIPS	C	S	AL	TF
Mostek	C	Co	AF	TF
Motorola	C, M	Co	AL	TL
National Semi	C	Co	AL	TL
NEC	C	Co	AF	TF
NCR	C	S	AF	TF
PACE	M	Co	AF	TL
Samsung	C	Co	AF	TL
Signetics	C	Co	AF	TF
Texas Instruments	C, M	Co	AL, AF	TL
Toshiba	C	Co	AF	TL
UTMC	M	S	AL	TL
Westinghouse	M	S	AF	TL
Zilog	C, M	Co	AL	TL

Intel and Motorola processors have been licensed to other firms in both commercial and military markets. These licensees include Advanced Micro Devices (AMD) and Harris, among others. While licensees continued to improve on the original ICs, sometimes beyond the original firm's improvement efforts or sale of a particular product, they are still "architecture followers," although some, like Harris, are classified as technology leaders.

Although Intel and Motorola have dominated commercial markets, they have had less control over military markets, in part because of the government's promulgation of

MIL-STD-1750A architecture for 16-bit microprocessors.[1] Texas Instruments (TI) has played an important part in the military market by introducing 1750A microprocessors fabricated with advanced technology, as well as microprocessors based on original architecture. These chips appeared in military systems manufactured by TI and other military contractors. Because of its active sales to other firms, TI is classified as a component-oriented supplier.

Systems firms have not made major contributions to commercial CISC markets, although IBM, AT&T and Hewlett-Packard have had active microprocessor R&D programs,[2] and AT&T has sold some microprocessors in components markets. The dominant role of Intel and Motorola, the abundance of software written for those processors, and the desire of the users to share software costs between families of systems, even if members of families are produced by different systems suppliers, have led to the eclipse of CISC microprocessors produced by systems firms. These firms have relied on microprocessors produced by component-oriented firms in their systems products, and even obtained licenses for those processors in some cases.

The relative contributions of systems- and component-oriented firms is more equal in the market for reduced-instruction-set computing (RISC) ICs. While it is too early to tell who will win the race for dominance there, it is clear that SPARC and MIPS R2000/3000 chips, both designed by systems firms, are important players. Sun Microsystems and MIPS Inc., both systems firms concentrating on the production of computers and workstations, can be considered architecture leaders, but do not necessarily lead in the fabrication technology. Component-oriented firms like Cypress Semiconductor, LSI Logic, and Bipolar Integrated Technology have taken the lead in implementing RISC architectures developed by Sun and MIPS with advanced technologies developed in-house.

Motorola and Intel are interesting to observe in the RISC market because they have not only introduced unique architectures, but have used their experience with CISC processors to produce chips in technologically advanced, highly integrated implementations. Although there has not been any indication that they are willing to license their RISC processors in commercial markets, they have licensed them to systems firms in military markets. Some of their second sources include Hughes and Thomson.

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[1]All microprocessors built to execute the DoD MIL-STD-1750A architecture are considered architecture followers.

[2]All these firms have presented papers on advanced microprocessors at international conferences, such as the International Solid State Circuits Conference.

PRODUCT EVALUATION

The second step in the analysis is an examination of microprocessor products along the three dimensions of the industry as it was segmented in Figure 1. The evaluations, presented below, include five microprocessor characteristics: clock speed, feature size, integration level (transistor count), instruction throughput (million instructions per second), and introductory price (price at sampling).

Commercial vs. Military

Both the Intel 8086 and the Motorola 68000 were introduced in the late 1970s. By 1981, the two firms were fighting for market dominance by signing multiple second source agreements and introducing product improvements. Performance differences between commercial and military processors were not great at that time. The Intel 8088 was rated at 0.33 mips and Motorola's 68000 at 0.35 mips[3] vs. 0.27 mips for TI's 9989. All three processors operated at approximately 4 MHz and were fabricated with approximately 3-μm features. The 8086 was manufactured in NMOS, the dominant manufacturing technology at the time, while the 68000 was manufactured in CMOS, a technology which was just starting to come into wide use.

By 1984, differences between commercial and military processors increased. While Intel and Motorola were introducing faster versions of the 32-bit 80286 and the 68020, the TI 9989 was the only JAN-qualified[4] 16-bit microprocessor on the market, and no 32-bit microprocessors were so qualified. Late in 1983, Harris introduced a rad-hard version of the 16-bit 8086. The performance range for the Intel and Motorola processors was about 2 to 3 mips with clock rates in the 8 to 12 MHz range, and 2-μm CMOS was the dominant fabrication technology in commercial markets. The Harris 80C86 was also fabricated in CMOS. It did, however, contain some features that commercial processors did not have, including reduced power operation. The Harris 80C86 was designed to operate at 5 MHz over the entire military temperature range.[5] If power were reduced (due to failure of power supply, for example), power use by the microprocessor could be

[3]*Motorola's 68000 Family*, Motorola, Inc., p. 8.

[4]JAN (which stands for Joint Army Navy) qualification is the most stringent qualification for military microelectronics. JAN-qualified ICs are qualified under MIL-STD-38510, which is a several-years-long process because the circuit must be tested for every possible combination of inputs and outputs. MIL-STD-883B is much less stringent, and most suppliers that sell to military markets sell under that qualification procedure.

[5]W. J. Niewierski, "Microprocessor Family Turns to Low-Power CMOS," *Defense Electronics*, June 1983, p. 132.

reduced by reducing clock speed to as low as 100 kHz while maintaining integrity of operations. In fact, the clock could be stopped altogether if necessary, and static design would maintain data as long as the circuit received standby power. By contrast, the minimum clock speed for the commercial NMOS 8086 was 2 MHz and its dynamic design required the clock to operate for data retention.

In 1986, the first chips qualified under the VHSIC Program became available in the military market. In July 1986, TI qualified a very fast implementation of the DoD 1750A architecture which, at 4 mips, compared favorably with the first commercial RISC processors which were coming out about that time. It was produced in 1.25 μm CMOS operated at 25 MHz, smaller line widths and higher clock speed than commercial microprocessors of that period. The Intel 80386, introduced into the commercial market at the end of 1985, was rated at 3 to 4 mips at 16 MHz and fabricated in 1.5 μm CMOS. Motorola's 68030, which was introduced toward the end of 1987, would be rated at 6 mips and would be produced in 1.2 μm CMOS, but in 1986 it was still under development. The earlier generation Motorola processor, the 68020, had moved out into military markets by that time.

TI also introduced a radiation-hard version of their 16-bit 9000 microprocessor in 1985, manufactured in 2-μm bipolar, optimized for radiation hardness rather than performance, and rated to perform 0.55 mips at 9 MHz.[6] The 9989 had radiation tolerance of 10^4 rads total dose; the TI 9000 introduced in 1985 had radiation tolerance of 10^6. The highest radiation-hardness requirement, part designation H, specified in 1987, was 10^6 rads total dose,[7] although further improvements in radiation tolerance of microprocessors were under development in government laboratories.

By 1989, the shakeout in the commercial CISC microprocessor market was complete. Intel and Motorola dominated the market and reasserted their dominance with the introduction of the 80486 and the 68040, respectively. The Intel 80486, introduced in early 1989, is rated at 15 mips at 25 MHz and fabricated with 1 μm CMOS. The Motorola 68040 rated at 20 mips at 25 MHz, fabricated in 0.8 μm CMOS.

In the military market, several implementations of the 1750A were introduced in 1988, including one by the United Technologies Microprocessor Center which emulated both the 1750A architecture and a RISC architecture. The military CISC market was still one generation behind the commercial market in 1989--Intel qualified its 80386 for the

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[6]"Technology '86: Solid State," *IEEE Spectrum*, January 1986, p. 56.

[7]*Design Handbook for TREE*, Chapter 7--Hardness Assurance, Kaman Sciences Corporation, DNA-1420H-7, October 30, 1987, pp. 7-20.

military market, even as it was introducing the next-generation processor in the commercial market.

However, a new element was now in play in the commercial market: RISC microprocessors, which were just starting to appear in 1986, had proliferated, and their performance improved to the point that it became comparable to the most advanced CISC processors. Performance of 20 mips for RISC chips is not unusual: LSI Logic's version of MIPS R3000 achieves that performance, as does Cypress Semiconductor's version of SPARC. With RISC as the apparent way of the future, both Intel and Motorola introduced their own RISC processors, despite the incompatibility of RISC processors with the existing CISC software bases. Intel's 80860, with its 64-bit-wide buses and over a million transistors, was shown to run at 33 mips under most circumstances, and as fast as 150 mips under specialized conditions[8]--the best performance on the market at the time. Motorola's chip, the 88000, performed comparably to other RISC processors, 14 to 20 mips.

While RISC was initially greeted without great enthusiasm by the military, by 1989 it was a "hot" technology. The MIPS R3000 architecture was selected as one of the standards for military avionics computers. MIPS-based processors are being used by Unisys on the Northrop prototype for the Advanced Tactical Fighter, as well as by TI and Hughes on the McDonnell Douglas LHX prototype. Intel's 80960 (the embedded control version of the 80860) was selected as the other standard for military avionics. Hughes Aircraft's 80960-based RISC processor won the competition for the Lockheed prototype of the Advanced Tactical Fighter. The Army has expressed a preference for MIPS-based ground terminals for its Joint Surveillance Tracking and Attack Radar System (JSTARS).

As usual, radiation-hard versions of RISC processors are likely to be several years behind the ones which are not radiation-hard. The contracts for the RH-32 radiation-hard RISC processor were awarded in January 1990,[9] so the production of chips is still several years away.

With a general comparison of military and commercial processors in place, let us now examine each of the processor characteristics indicated above and see how military and commercial processors compare with respect to each parameter chosen.

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[8]The processor must execute one integer operation and two-floating point operations simultaneously in order to achieve 150 mips rating.

[9]TRW and Honeywell recently won parallel $8 million contracts to develop the RH-32 radiation-hardened 32-bit RISC processor for space applications. [*Electronic News*, January 29, 1990, p. 8.]

Clock Speed

Figure 6 charts processor clock rates for commercial and military microprocessors vs. time. Both CISC and RISC processors are included. Although there are considerably fewer data points for military processors than commercial ones, a few patterns appear in the chart. Prior to 1982, commercial and military processors operated at approximately the same speeds. In fact, the military Fairchild 9445 was clearly an outstanding performer along this dimension.

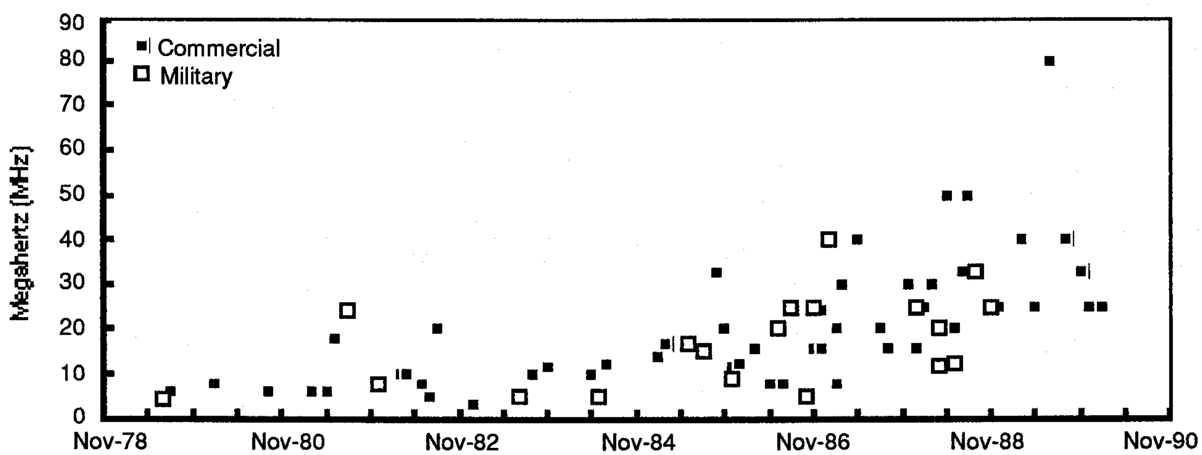

Fig. 6--Microprocessor clock rates, commercial vs. military

Military processor clock speeds started showing a noticeable increase after 1985, coincident with the introduction of VHSIC-like chips[10] into the military market, while commercial processors also continued their steady upward progress. Since that time, clock rates of military processors have been about the same as those of commercial processors. In several cases, military processor speeds on the high end lead commercial processors (i.e., appear to the left of similar commercial processor speeds). However, the recent higher-clock-rate processor introductions are commercial, and lower-clock-rate processors are military. A likely explanation for this is that commercial users have

[10]I am using "VHSIC-like chips" rather than "VHSIC chips" because not all ICs developed to VHSIC specifications were developed under the VHSIC Program.

adopted higher-clock-rate RISC processors while military users have not done so to the same extent.

Comparing RISC and CISC processors is not entirely fair, however. For this reason, Figure 7 excludes RISC processors, both military and commercial. The same pattern remains, however: military processors appear to lead in clock speeds during 1986 and 1987, but generally lag during the 1982-1986 period, and after 1987 as well. The high clock speeds reached by military processors in 1986 and 1987 are a reflection of processors built to VHSIC clock speed specifications (25 MHz) coming into the market. The early versions of the most advanced CISC processors, the 80486 and the 68040, also operated at 25 MHz, which reduces the apparent differences between commercial and military processors.

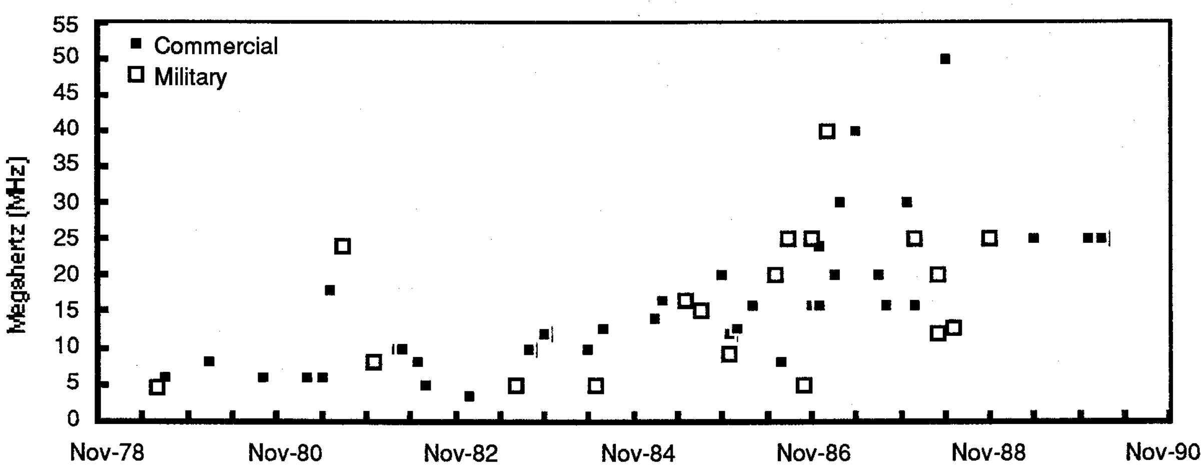

Fig. 7--CISC microprocessor clock rates, commercial vs. military

Feature Size

Figure 8 charts minimum feature sizes for commercial and military processors, in microns. Little information is publicly available about this characteristic of early military processors. It is clear, however, that the general technology trend has been toward smaller and smaller feature sizes, with occasional outliers on either high or low side. (The early commercial processor with 1.5-μm technology, which appears as an outlier on the chart, was developed by Hewlett-Packard.) As discussed above, a number of military processors were introduced with larger feature sizes than those in their commercial counterparts because larger transistors are necessary in order to achieve greater hardness

against some types of radiation hazards. Several military microprocessors were introduced with 1.25 μm features in 1986 as VHSIC Phase 1 ICs entered the market. It was during that period in 1986 that military processors led their commercial counterparts along this dimension. Commercial processors caught up quickly, however.

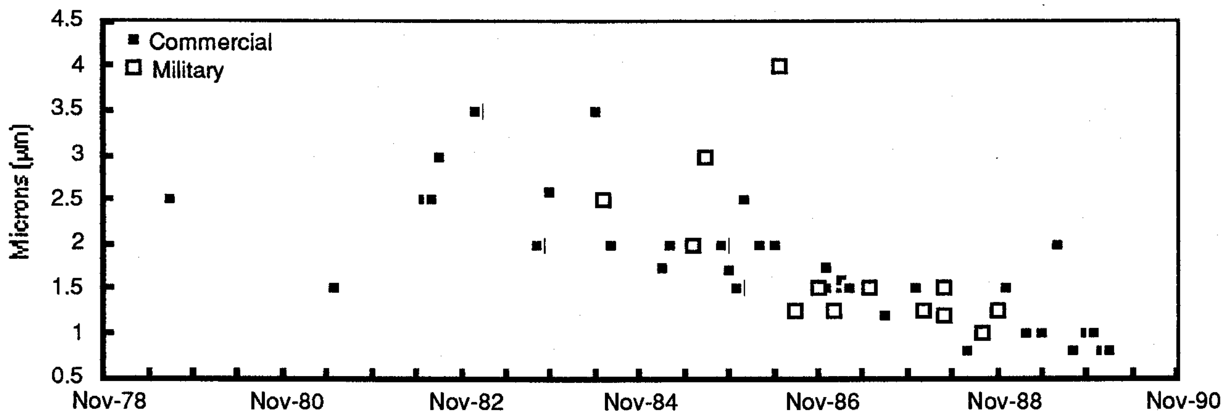

Fig. 8--Microprocessor feature size, commercial vs. military

As commercial markets moved toward the use of RISC processors, the need for smaller and smaller feature sizes has been relaxed somewhat. A recent commercial "outlier" on the high side (2-μm) is the Bipolar Integrated Technology's (BIT) implementation of the SPARC microprocessor, a conservative approach to manufacturing technology, permitted by the fact that the SPARC architecture can be implemented using relatively few transistors. Commercial CISC processors, like the Intel 80486 and the Motorola 68040, continue to require fine line widths and high transistor counts to implement their architectures. This is reflected in Figure 9 which excludes both commercial and military RISC processors.

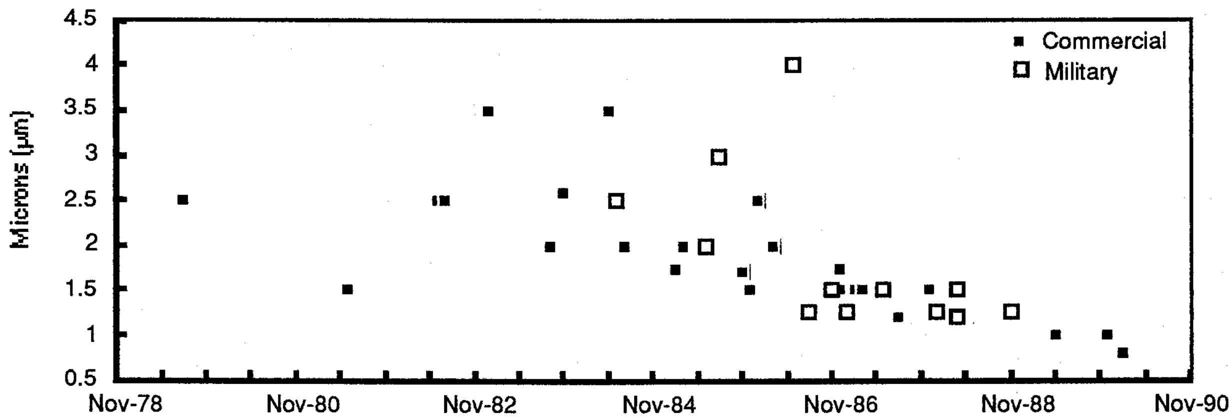

Fig. 9--CISC microprocessor feature sizes, commercial vs. military

Integration Levels

Figure 10 shows the numbers of transistors which form part of various commercial and military microprocessors.[11] There are few data points for military processors. However, the highest transistor counts for currently available microprocessors are commercial--the Intel 80486 and the Motorola 68040. The available observations for military processors are concentrated between 1985 and 1988--the time when chips which should have taken advantage of VHSIC R&D results should have been coming on line. There is no visible difference between commercial and military transistor counts during that period, however. Transistor counts for commercial processors are the same or higher than the counts for military processors.

[11]In cases where the processor is part of a multi-chip set, the transistor count reflects only the number of transistors on the processor and excludes the other chips in the set.

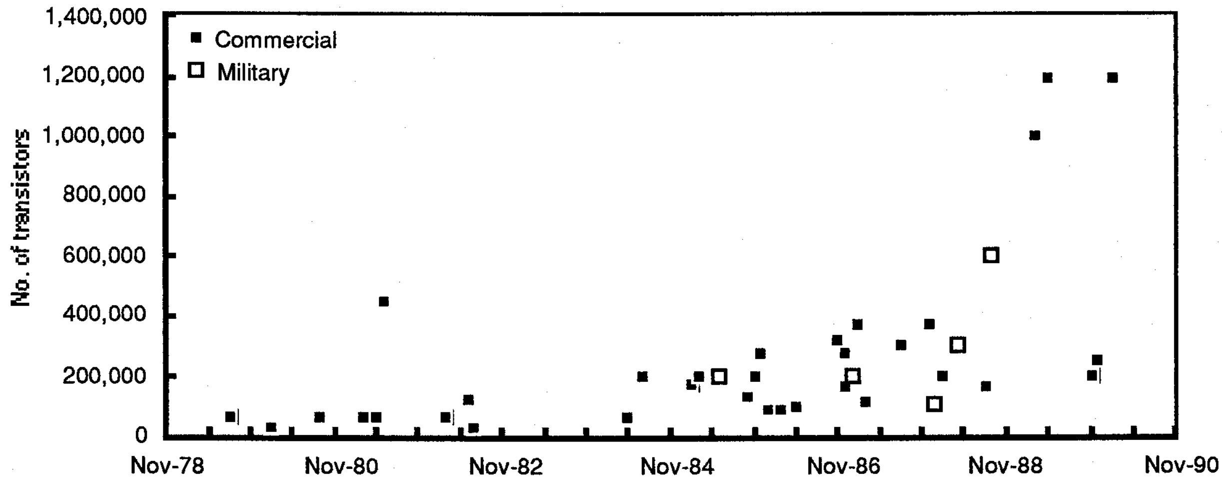

Fig. 10--Microprocessor integration levels, commercial vs. military

The differences between commercial and military transistor counts are magnified when commercial RISC processors are removed from the picture. Figure 11 shows only CISC processors. Since RISC architectures require fewer transistors to implement, these appeared as "retrogressive" recent introductions in Figure 10. Figure 11 shows that the military is about a generation behind in integration levels when compared with commercial CISC processors.

Instruction Throughput

Figure 12 shows instruction throughput for commercial and military microprocessors in millions of instructions per second (mips). Since a mips comparison of CISC and RISC processors is not meaningful, and since the majority of RISC processors on the market today are commercial, only CISC processors are included in the figure.

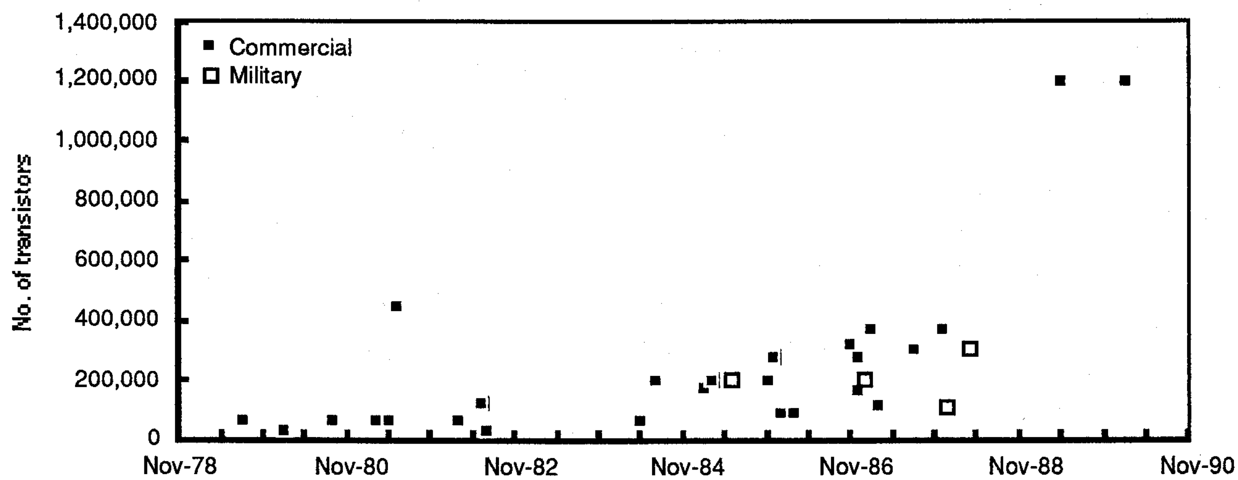

Fig. 11--CISC microprocessor integration levels, commercial vs. military

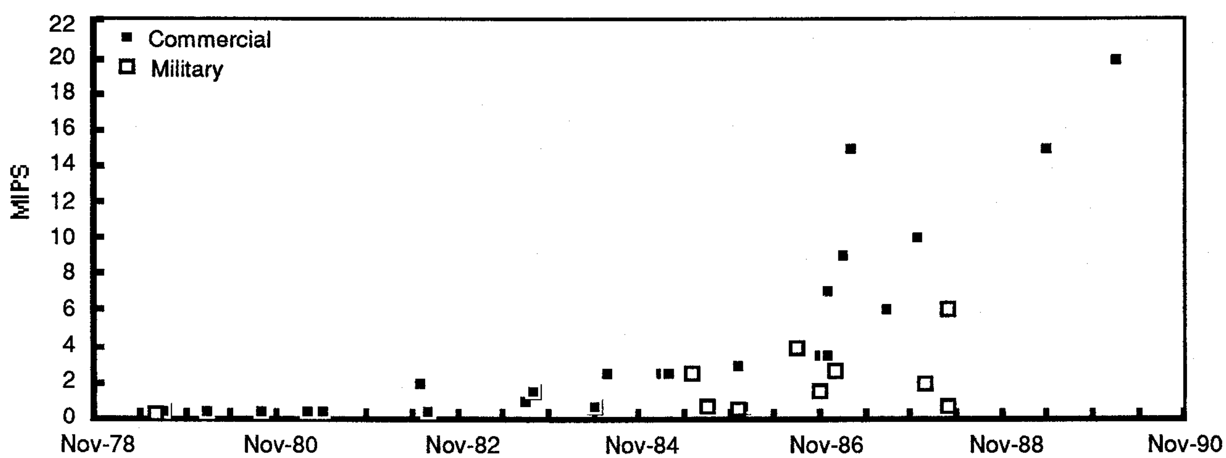

Fig. 12--CISC microprocessor performance, commercial vs. military

Although data are sparse, it appears that performance of military microprocessors has remained fairly stagnant while the performance of commercial processors has taken off in the past five years. A physical explanation for this may be the fact that most of the military microprocessors shown in the figure are still implementations of the 16-bit MIL-

STD-1750A architecture, while commercial processors have moved on to more advanced 32-bit architectures.

As discussed above and in Appendix B, the very high performance processors have RISC architectures, and it is not likely that the military can achieve the same levels without using the same approach. A comparison of military and commercial RISC cannot be made at this time, however, because RISC is just entering the military market.

Sampling Price

Figure 13 shows the price of commercial and military microprocessors at the time of introduction, in constant 1982 dollars. It is quite clear from the chart that commercial microprocessors have consistently been introduced at lower prices during the period under analysis. In some cases the price difference has not been significant; in other cases it amounted to more than a factor of two.

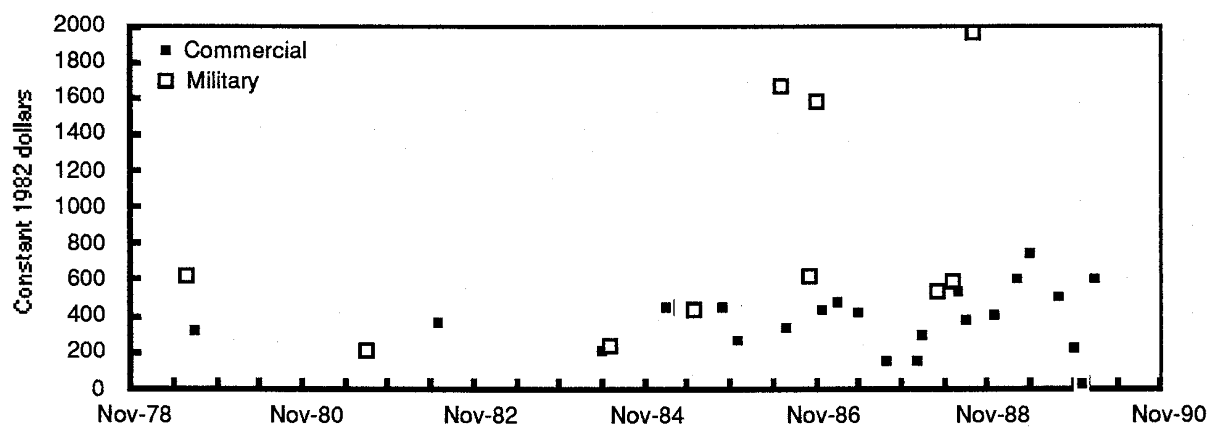

Fig. 13--Sampling price, commercial and military microprocessors

Figure 14 is an attempt to normalize introductory price with respect to performance--it shows the ratio of price and performance ($/mips) for commercial and military processors. Although data are sparse and widely scattered, the previous impression remains: data points for military processors never appear below comparable commercial points, and usually appear above them.

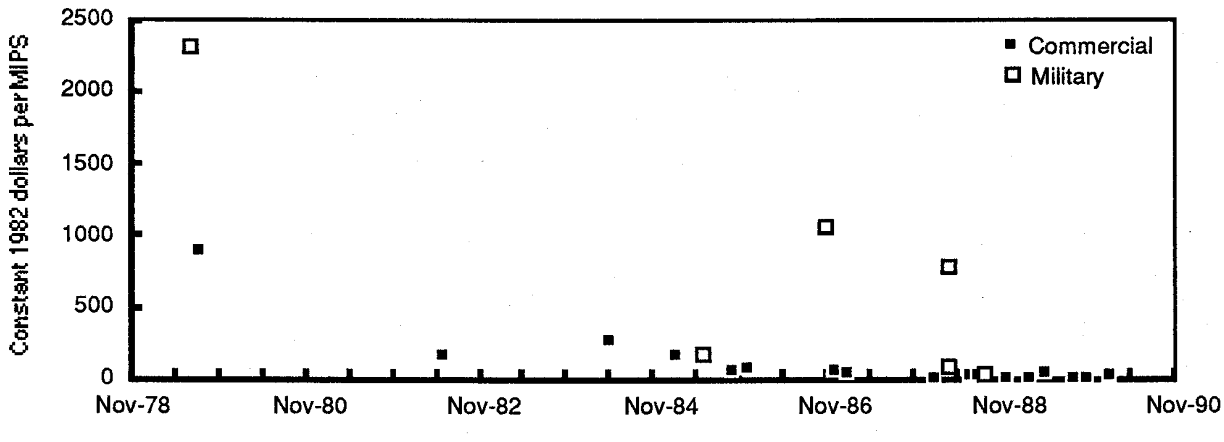

Fig. 14--Microprocessor price-performance ratio, commercial vs. military

Integration of Multiple Characteristics

Above we examined individual processor characteristics, and it appeared that in every case commercial processors were either ahead of military processors or at about the same stage of development. However, it is possible that manufacturers sacrifice performance along one dimension in order to improve performance along a different dimension. In fact, it is possible that if commercial and military manufacturers make different trade-offs, the overall differences between the state of development in commercial and military processors will disappear. In order to determine whether or not this is the case, a multiple regression analysis was performed, relating all processor characteristics to the month of introduction, and including a dummy variable to differentiate commercial and military processors. The results of the regression analysis are shown in Table 4.2.

The table includes results of four regressions. The first one, including all variables of interest plus military dummy, does not fit the data well. None of the coefficients is significant. Of the remaining regressions, regression 3 has coefficients which are all significant, and Adjusted R^2 which is somewhat smaller than that for regression 2, but with one less variable. In fact, adding a variable which differentiates CISC and RISC processors in regression 4 further reduced fit. Let us, therefore, examine regression 3 more closely.

Table 4.2

REGRESSION RESULTS--COMMERCIAL VS. MILITARY MICROPROCESSORS

Variables	Regression 1	Regression 2	Regression 3	Regression 4
Constant	-65.541 (0.659)	271.443 (0.000)	210.540 (0.000)	214.821 (0.000)
Clock (FI)	- 6.263 (0.665)	0.235 (0.414)	0.565 (0.001)	0.487 (0.006)
Feature Size (FI)	1.139 (0.065)	-22.600 (0.001)	-22.111 (0.000)	-21.195 (0.000)
Ln No. Transistors	18.898 (0.081)	- 3.626 (0.378)		
Military Dummy	9.845 (0.612)	- 1.503 (0.809)	11.218 (0.007)	12.276 (0.004)
CISC Dummy				- 7.070 (0.168)
MIPS	0.684 (0.365)			
Price ($82)	- 0.038 (0.203)			
$/MIPS ($82)		- 0.086 (0.000)	- 0.040 (0.000)	- 039 (0.000)
Adjusted R^2	0.723	0.883	0.801	0.797

NOTE 1: Numbers in parentheses represent the significance of the coefficient, i.e. 0.010 means that the coefficient is significant at the 1% level.

NOTE 2: "FI" in the variable name means that the data used in the regression was augmented by the technique discussed in Section II.

We can note the following. First, processor characteristic variables have expected signs. Variable "Clock" has a positive sign, i.e., processors with higher clock speeds are introduced later than processors with lower clock speeds. "Feature Size" has a negative sign--smaller feature sizes come later than larger feature sizes. The same is true of \$/mips. Second, the military dummy has a significant positive sign. Given the fact that multiple characteristics are involved, we can interpret the positive sign of the military dummy coefficient as an indication that when we compare military and commercial processors with similar characteristics, military processors are generally introduced later than commercial processors. The size of the coefficient, 11 months, tallies well with the results of interviews with industry representatives who have indicated that it takes approximately that long to test processors to military specifications and to design packaging to meet the more extensive temperature range.

Hypothesis 1 As It Applies to Microprocessors

As the above comparisons of commercial and military microprocessors indicate, the military has, for the most part, been behind the commercial market in development and implementation. Except for the DoD-defined 1750A architecture, developed specifically for the military, military processors introduced during the 1980s have generally been based on commercial CISC processors created by commercial firms for commercial markets. The introduction of military processors has generally lagged behind the commercial introductions by approximately a year, and these processors have been considerably more expensive than their commercial counterparts.

There are two major areas in which the DoD's contribution might have been expected to have a significant effect on microprocessor development: funding of advanced architecture development and funding of manufacturing technology. Although DARPA funded RISC development, and although DoD has always been considered a customer in search of high-performance electronics, DoD's acceptance of computers based on RISC microprocessors came after these architectures were accepted in commercial markets. In fact, as discussed in Appendix B, one reason why the MIPS architecture was chosen as DoD standard was its popularity in commercial markets. Work on radiation-hard RISC chips is beginning only now, five years after the introduction of the first RISC ICs, which means that they will not be available for several more years, putting the DoD further behind commercial markets in the areas requiring rad-hard applications. DoD's significant contribution to the development of RISC has not translated into higher-performance processors for the military.

The other area of potential DoD contribution to microprocessor development was IC fabrication technology. The biggest DoD program over the past ten years which might have shown an impact here is the VHSIC Program. Of the major players in the microprocessor markets, only Motorola participated in both phases of the Program; Texas Instruments participated in Phase 1. Motorola, as part of a team with TRW, worked with bipolar technology in Phase 1 and a 0.5-μm CMOS process in Phase 2. Texas Instruments created a chip set during Phase 1 using mostly bipolar fabrication technology, which was used to fabricate a 1750A data processing module,[12] certified in July 1986. As the above charts indicate, though, the VHSIC Program allowed the DoD to catch up to the commercial industry, or perhaps to acquire a lead so slender that it eroded within a few months.

While it is safe to say that at least some of the fabrication technology developed by firms under the VHSIC Program and similar company-funded programs found its way into their commercial products, it is not clear just what the DoD contribution has been, other than "concentrating the effort" of various manufacturers on the move to submicron technology. VHSIC Phase 1 aimed at developing 1.25-μm line widths. By the time Phase 1 chips were being qualified in 1986,[13] 1.25- to 1.5-μm technology was already on the way into the commercial market--the Motorola 68030, fabricated in 1.2-μm HCMOS, was introduced during the following year. Technology developed under Phase 2 is still ahead of commercial markets, however: the most advanced microprocessors sold today are being fabricated in 0.8-μm CMOS, not in 0.5-μm technology developed for VHSIC Phase 2. Nothing comparable in the level of integration to the TRW/Motorola CPUAX with its 4 million transistors and its self-healing capability has even been attempted in the commercial market.[14]

Radiation hardness, the major difference between commercial and military microprocessors, was one of the issues specifically addressed in the VHSIC Program. However, it is not clear how much of the research performed in that program will get translated into actual circuits. TRW and Honeywell, both VHSIC Phase 2 participants, are now working on a rad-hard RISC microprocessor which will, presumably, be the

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[12]K. Julian, "Defense Program Pushes Microchip Frontiers," *High Technology*, May 1985, p. 51.

[13]VHSIC Program Office, Office of the Under Secretary of Defence for Acquisition,*VHSIC Annual Report for 1986*, 31 December 1986, p. 1.

[14]The CPUAX was developed for signal processing applications and will be discussed in the chapter on DSPs.

conduit for moving some advanced VHSIC technology into specific microprocessors for military and space markets.

It should be noted, however, that commercial microprocessors are going to become more radiation-tolerant with time. As discussed in Section II and the Appendix, bipolar circuits are not only faster, but have a higher radiation tolerance than those fabricated in CMOS. The general trend in fabrication technology is a shift from CMOS in the 1980s to bipolar and biCMOS in the 1990s, as commercial manufacturers pursue greater speed. In fact, several commercial manufacturers have already started implementing their microprocessors in bipolar. Although speed, not radiation tolerance, is the major attraction, radiation tolerance of commercial circuits will rise when they are fabricated with technologies which are inherently more radiation resistant.

Hypothesis 1 stated that commercial markets can be expected to be on par with or lead military markets in technology. The data support this hypothesis.

Generation Skipping

As was discussed above, military microprocessors have run a few months to several years behind their commercial counterparts. The reasons for this include the specialized nature of testing for military specifications as well as the specialized technologies relevant to some military applications. There is no evidence that military microprocessors were introduced before or even concurrently with commercial microprocessors of the same generation. There are no cases in which military microprocessors have led commercial developments. The transition in fabrication technologies has been gradual from 2 to 3 μm, common in the early 1980s, to 0.8 to 1.2 μm common today. It appears, therefore, that the data support Hypothesis 2, which stated that the government's strategy of skipping product generations does not produce advanced ICs faster than commercial evolutionary development.

Systems vs. Component Orientation

As discussed above, the market for general purpose CISC microprocessors has been dominated by Intel and Motorola--both component-oriented manufacturers. Even though some of the big systems houses have had licenses to manufacture other firms' microprocessors for their own uses or specific markets, systems firms did not generally pioneer CISC processors which were subsequently licensed to component producers. Nevertheless, systems firms have continued to do microprocessor research, as evidenced by papers presented by IBM, AT&T, and Hewlett-Packard at international conferences.

Systems firms guard the information about their R&D programs as proprietary, but the fact that they sell systems based on Intel and Motorola microprocessors demonstrates the extent to which they rely on component producers with respect to this product group.

The situation is different with RISC processors. RISC was developed by researchers at IBM, a systems firm, in the 1970s. Further research into RISC was performed at universities, and both MIPS and SPARC architectures are the outgrowth of university research. RISC did not become a phenomenon until MIPS Computers and Sun Microsystems, both systems firms, put a concerted effort into demonstrating the advantages of RISC-based systems over CISC-based ones. However, since both MIPS and Sun have extensively licensed their designs to component producers, and since Motorola and Intel have entered the fray with their own RISC designs, it appears possible that further advances will again be dominated by component-oriented firms.

Clock Speed

Figure 15 charts clock speeds for processors developed by systems- and component-oriented firms versus time. Clock speeds of processors introduced by systems firms are well behind those introduced by component-oriented firms. This is not surprising in light of the discussion above and in Appendix B. It is true even in the case of RISC microprocessors, which have been extensively licensed to component-oriented firms. Additionally, many of the processors shown in the chart as being introduced by systems firms are military processors, which were demonstrated above to have run generally behind commercial processors.

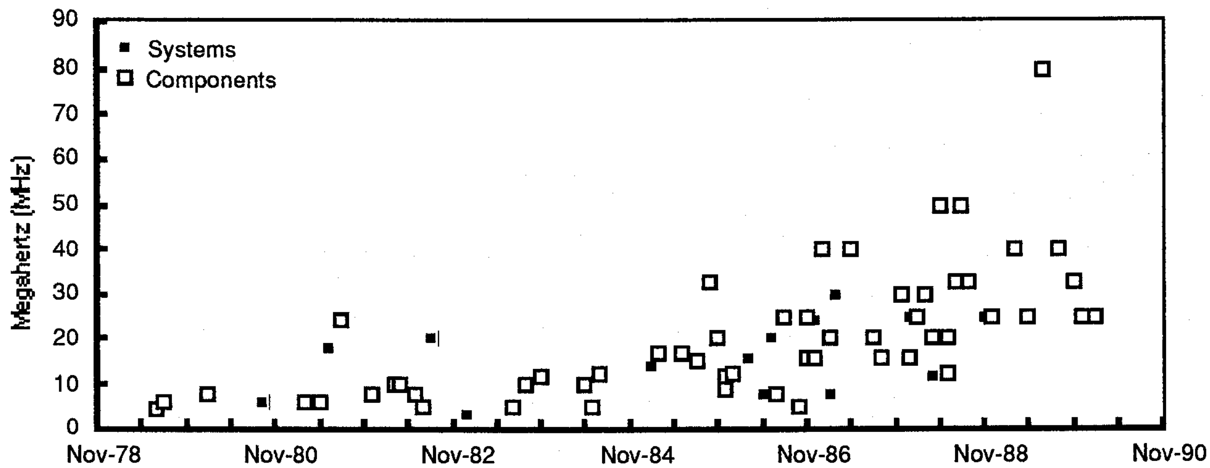

Fig. 15--Microprocessor clock speeds, systems- vs. component-oriented firms

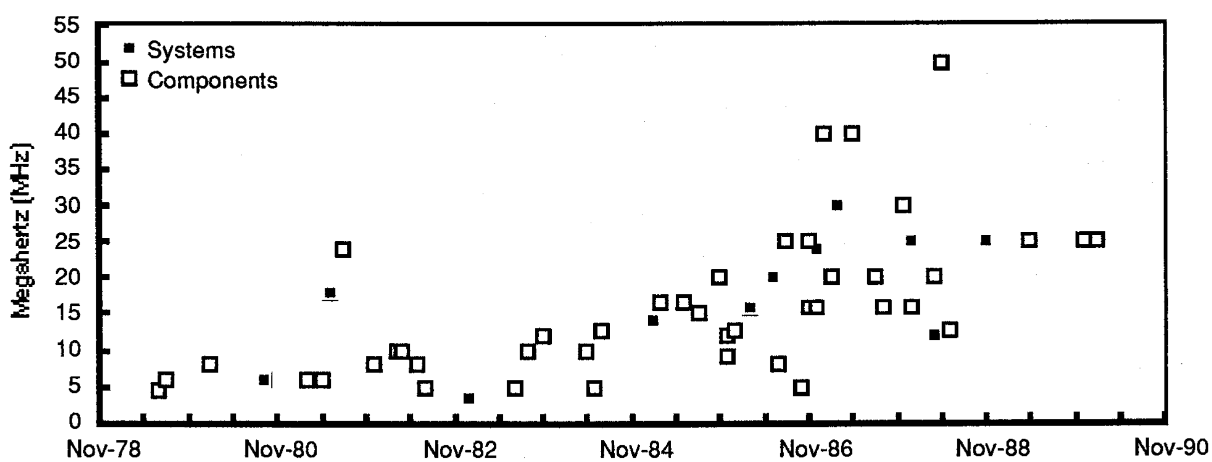

Fig. 16--CISC microprocessor clock speeds, systems- vs. component-oriented firms

In order not to prejudice the comparison, Figure 16 excludes RISC microprocessors. The pattern remains unchanged, however--processors introduced by systems firms are generally introduced with lower clock rates than those introduced by component-oriented firms.

Feature Size

Figure 17 shows feature sizes of microprocessors introduced by systems- and component-oriented firms. With the early exception of the Hewlett-Packard processor fabricated with 1.5-μm features, systems firms have generally been behind component-oriented firms in manufacturing technology, i.e., the data points for systems firms appear above and to the right of points for component-oriented firms. This has not been affected by the introduction of RISC processors into commercial markets because Sun Microsystems and MIPS Computers have licensed their architecture designs to component-oriented firms which have been implementing these architectures with advanced manufacturing technologies. Thus, component-oriented firms continue to lead in microprocessor feature sizes.

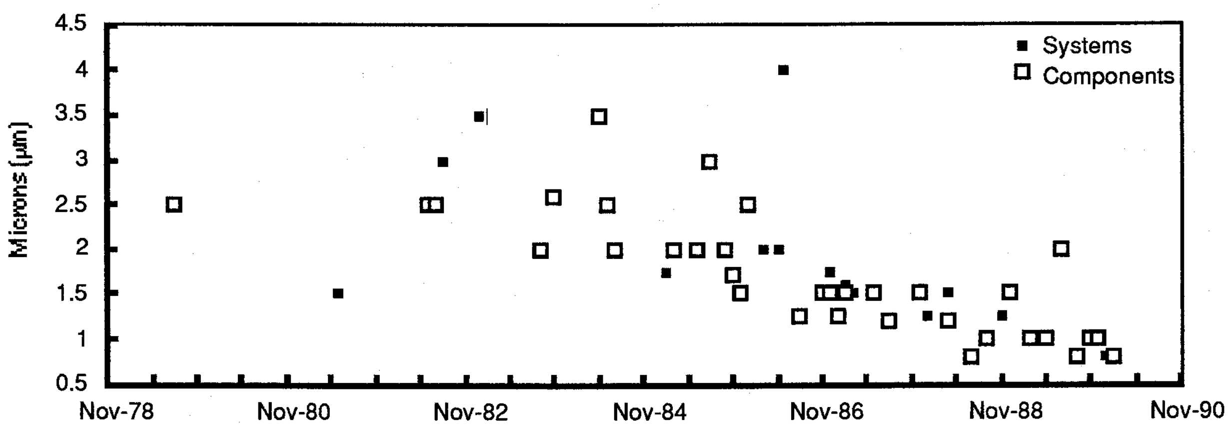

Fig. 17--Microprocessor feature size, systems- vs. component-oriented firms

Integration Levels

Figure 18 shows microprocessor integration levels. With the exception of the Hewlett-Packard processor which incorporated 450,000 transistors in 1981, systems firms have consistently lagged behind component firms in integration levels. In part, this can be traced back to the fact that many systems firms are military contractors, manufacturing chips which execute the older 1750A architecture, as opposed to 32-bit architectures common in commercial markets. Mostly, though, the relative positions of systems- and component-oriented firms reflects the dominance of component-oriented firms in the microprocessor product group.

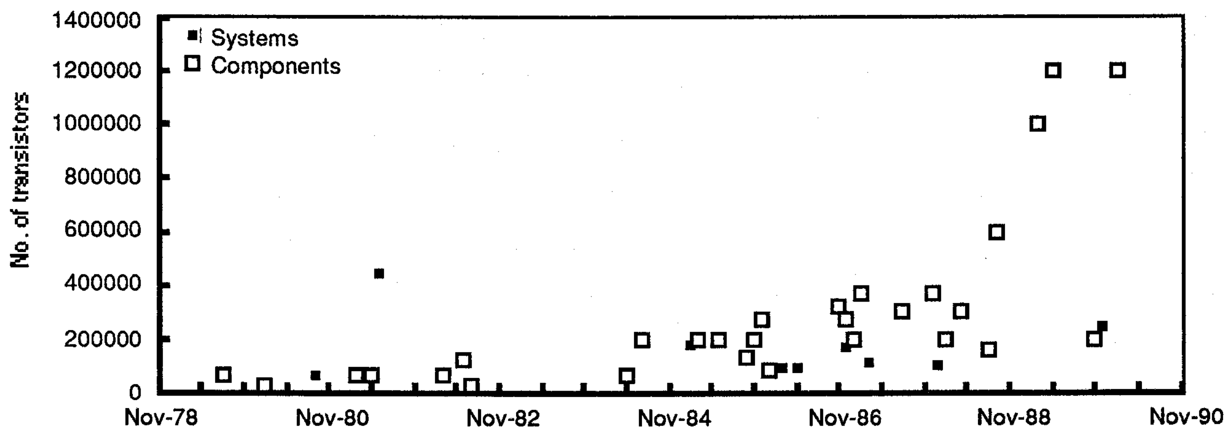

Fig. 18--Microprocessor integration levels, systems- vs. component-oriented firms

Instruction Throughput

Figure 19 shows instruction throughput for microprocessors introduced by systems- and component-oriented firms, in million instructions per second. Although data on systems-oriented firms are sparse, systems firms have introduced some high-performance processors in at least two cases: processors introduced by Hewlett-Packard in February 1987 and in January 1990. For the most part, however, systems firms produced ICs with smaller instruction throughputs than component-oriented firms, or the same throughputs later than those produced by component-oriented firms. This is true even in the case of RISC processors. For instance, the processors with the highest performance on the chart is Bipolar Integrated Technology's implementation of SPARC architecture.

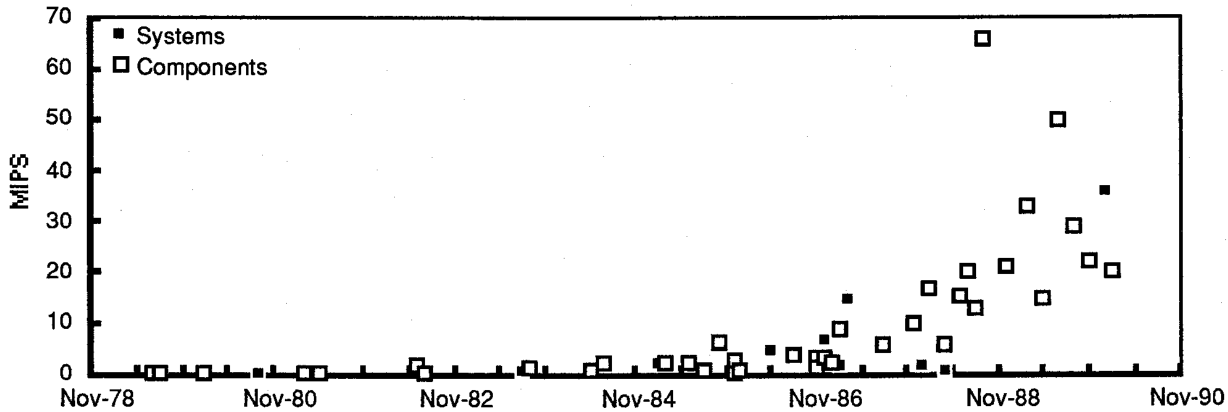

Fig. 19--Microprocessor performance, systems- vs. component-oriented firms

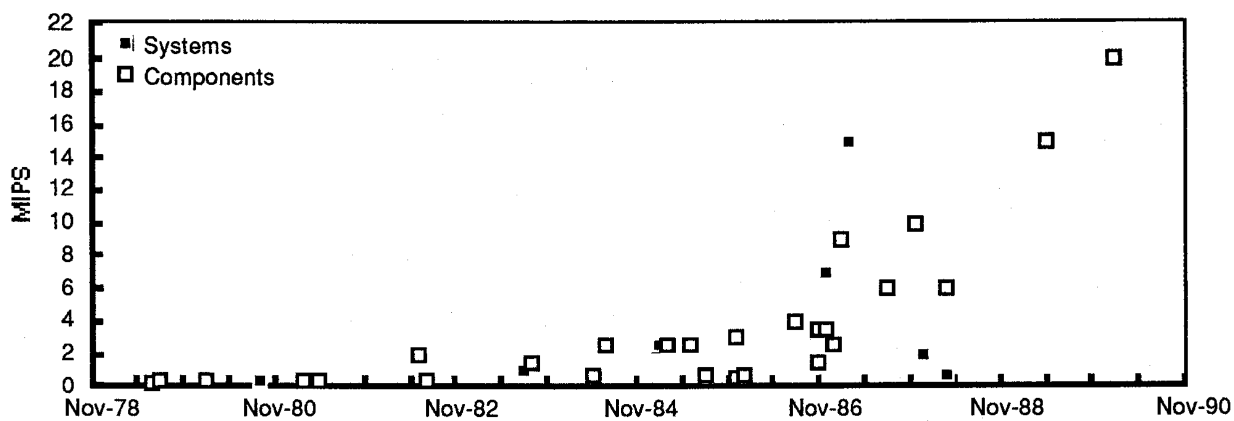

Fig. 20--CISC microprocessor performance, systems- vs. component-oriented firms

Figure 20 shows the same comparison as Figure 19, but with RISC processors taken out. The same conclusions can be drawn as above. The Hewlett-Packard processor is a clear stand-out, but otherwise the chart is dominated by component-oriented firms.

Introductory Price

Figure 21 shows introductory prices for microprocessors produced by systems- and component-oriented firms. Data on systems firms are sparse, especially before 1985, but

for the most part, processors introduced by systems-oriented firms were introduced at the same or slightly lower prices as those introduced by component-oriented firms. Figure 22 normalizes price of introduction with respect to processor performance and indicates that, when performance is taken into account, prices for microprocessors introduced by systems-oriented firms are still about the same as those for component-oriented firms, in cases where prices for components produced by systems-oriented firms are known.

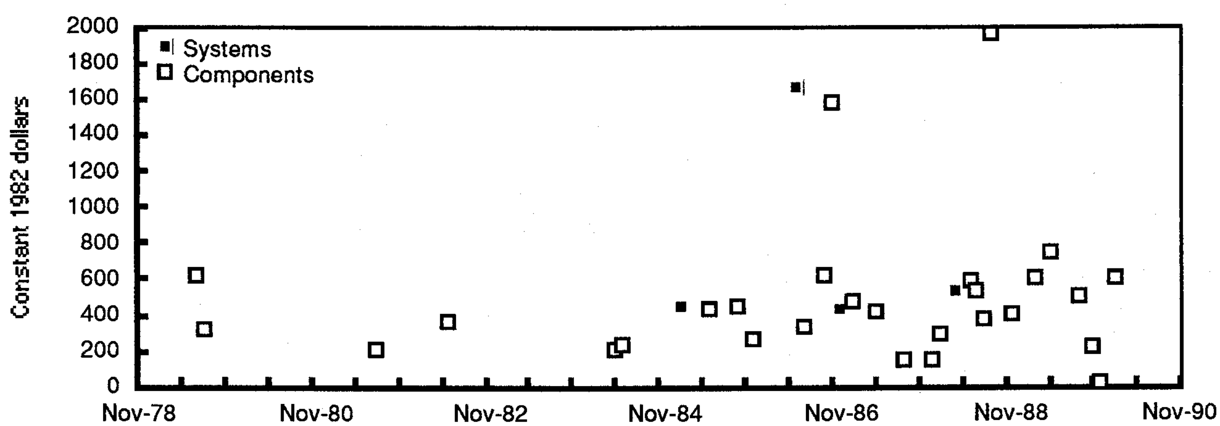

Fig. 21--Introductory price of microprocessors, systems- vs. component-oriented firms

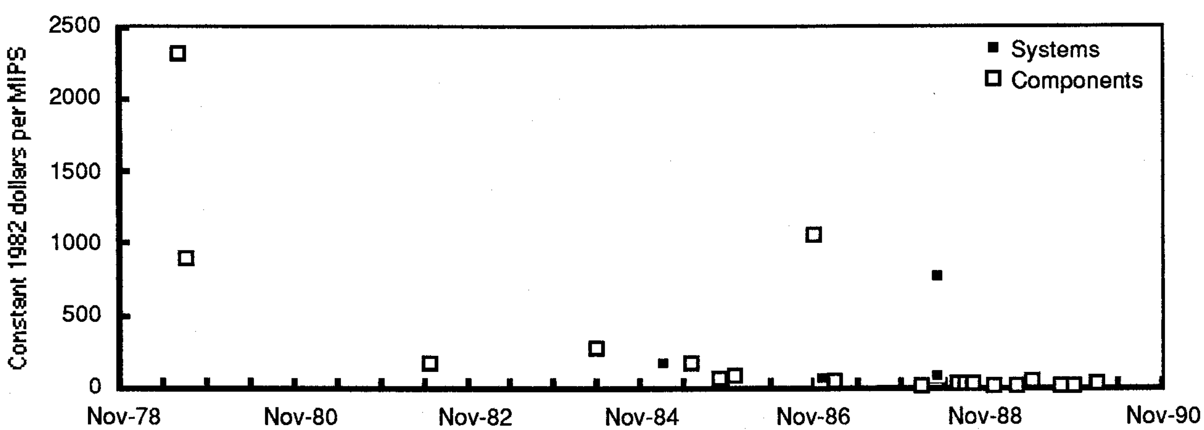

Fig. 22--Microprocessor price-performance ratio, systems- vs. component-oriented firms

Integrating Multiple Characteristics

As in the case of military and commercial microprocessors, it is necessary to see whether there are differences in the tradeoffs made by different types of firms. Table 4.3 shows the results of multiple regression analysis for systems- and component-oriented firms. It includes three regressions: one which includes only the systems dummy, and two more which add the military and CISC dummies. The systems dummy is not significant in any case.

Hypothesis 3 As It Applies to Microprocessors

Hypothesis 3 stated that funding military microelectronics R&D through systems-oriented firms delays the creation of most advanced components because systems firms do not have improvement of components as a priority. There is some support for the hypothesis in the data. The charts of the data indicate that systems firms appear to be slightly behind components firms in introducing processors with similar characteristics (with the notable exception of Hewlett-Packard), although the difference is not significant in multivariate regression analysis. The evidence which supports the hypothesis can be used to counter the contention that systems firms are likely to develop more advanced microprocessors because they are driven by systems considerations, the reasoning behind the government's investment strategy in microelectronics R&D.

Table 4.3

REGRESSION RESULTS--MICROPROCESSORS PRODUCED BY SYSTEMS- VS. COMPONENT-ORIENTED FIRMS

Variables	Regression 5	Regression 6	Regression 7
Constant	213.547 (0.000)	209.654 (0.000)	215.728 (0.000)
Clock (FI)	0.557 (0.002)	0.579 (0.001)	0.514 (0.007)
Feature Size (FI)	-23.152 (0.000)	-22.273 (0.000)	-22.341 (0.000)
Military Dummy		11.303 (0.007)	
CISC Dummy			- 4.478 (0.407)
System Dummy	2.885 (0.498)	3.188 (0.434)	3.182 (0.475)
$/MIPS ($82)	- 0.036 (0.000)	- 0.040 (0.000)	- 0.035 (0.000)
Adjusted R^2	0.781	0.800	0.788

NOTE 1: Numbers in parentheses represent the significance of the coefficient, i.e., 0.010 means that the coefficient is significant at the 1% level.

NOTE 2: "FI" in the variable name means that the data used in the regression was augmented by the technique discussed in Section II.

RISC is interesting in this respect. Several RISC architectures exist today. IBM, an early participant in RISC research, is a systems firm. The Intergraph Clipper architecture is an outgrowth of early research performed at Cray Research, a systems firm. RISC research funded by DARPA ended up in the creation of MIPS and Sun Microsystems, both systems firms. While RISC architectures significantly improved performance, it appears that within the RISC arena component-oriented firms produce ICs that are no less and sometimes more advanced than those produced by systems-oriented firms, lending more support to Hypothesis 3.

Leaders vs. Followers

As mentioned at the start of this Section, firms which produce microprocessors can choose to be leaders or followers with respect to processor architecture or with respect to manufacturing technology. Each choice is addressed separately within the subsection dealing with a given device characteristic.

The general purpose microprocessor market has been dominated by Intel and Motorola, both using leader strategies in architecture and technology. Until the 80386 and the 68030 were introduced, both firms licensed their microprocessors extensively. As a result, the list of manufacturers which produce a given Intel or Motorola product changed over time. Second-source firms continued to improve earlier-generation products they licensed and have introduced versions which operate at higher speeds than those produced by original manufacturers without making basic alterations to the architecture. These products are, therefore, the descendants rather than copies of earlier products.

Table 4.4 shows one view of microprocessor evolution by listing the worldwide leaders in microprocessor sales in 1985. Although Intel invented the 8-bit microprocessor, by 1985 these were no longer leading edge devices and Intel's share of the market was relatively small. NEC, one of Intel's second sources, led world production with the largest market share. Intel and Motorola did lead in the production of 16-bit MPUs, the microprocessors which were at the height of popularity at the time. Motorola had by far the greatest share of the 32-bit market--it led the introduction of these advanced devices into the marketplace.

Table 4.4

1985 WORLDWIDE LEADERS IN MICROPROCESSOR SALES

8-bit MPUs			16-bit MPUs			32-bit MPUs		
	Mkt Shr	Approx Sales ($Mil)		Mkt Shr	Approx Sales ($Mil)		Mkt Shr	Approx Sales ($Mil)
NEC	16%	$28.0	Intel	39%	$93.0	Motorola	60%	$10.0
Toshiba	14%	25.0	Motorola	18%	43.0	National	30%	5.0
Sharp	10%	18.0	NEC	10%	24.0	Others	10%	1.8
Intel	8%	14.0	AMD	6%	14.0			
Zilog	7%	13.5	Others	27%	65.0			
Others	45%	79.5						
Total		$178.0	Total		$239.0	Total		$16.8

SOURCE: Dataquest Inc. quoted in "Microprocessors: Who Buys What and Why," *Electronic Business*, October 15, 1986, p. 90.

Let us now examine the characteristics of microprocessors introduced by firms employing leader and follower strategies.

Clock Speed

Figure 23 shows clock speed versus time for processors produced by architecture leaders and followers; Figure 24 shows clock speeds for technology leaders and followers.

It is not surprising that clock speeds of processors introduced by architecture leaders and followers are intermixed, apparently randomly. As discussed above, architecture followers produce the same processors as architecture leaders, just at a different point in time. In fact, the ability to concentrate on manufacturing technology rather than architecture development has enabled some firms to introduce chips with higher clock speeds than chips introduced by architecture leaders during the same period. The Fairchild 9445 was an outstanding performer along this dimension in 1981; the DEC Micro/J11 was outstanding in 1982; the BIT implementation of SPARC is the highest clock-speed microprocessor in 1989.

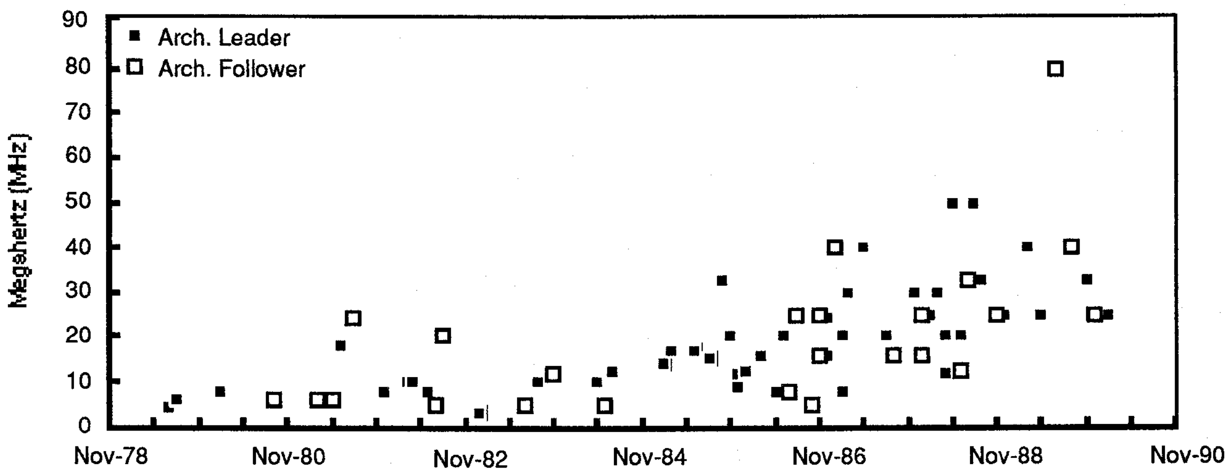

Fig. 23--Microprocessor clock speeds, architecture leaders vs. architecture followers

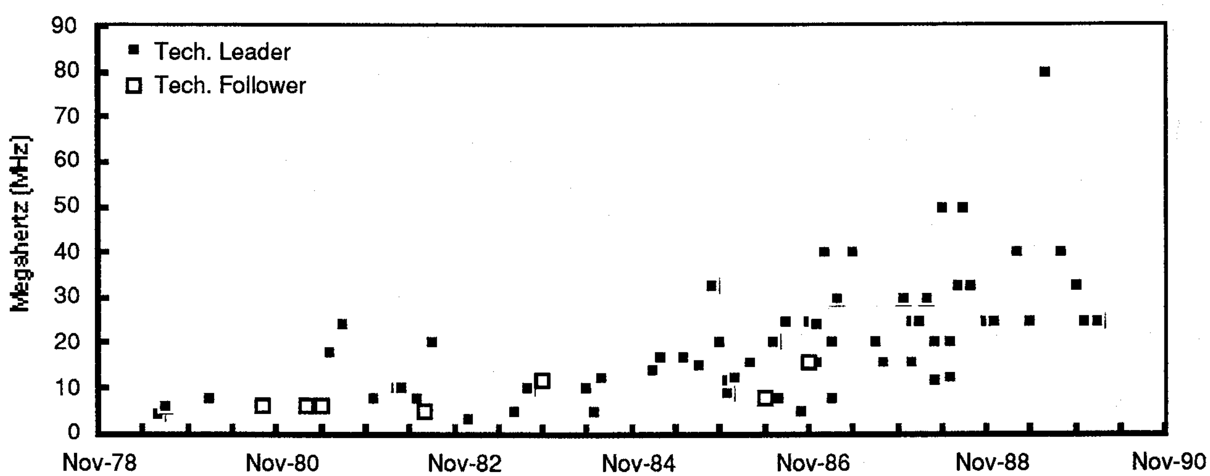

Fig. 24--Microprocessor clock speeds, technology leaders vs. followers

Data on technology followers are scarce, but the indication from available data is that technology followers produce microprocessors with about the same clock speed as technology leaders, but later. This is what one would expect to see from the definitions of technology leaders and followers.

Feature Size

Figure 25 shows feature sizes for microprocessors produced by firms employing architecture leader and architecture follower strategies. The data points are pretty well mixed, with smaller feature sizes being recently introduced by architecture followers. The explanation for this is that architecture followers can concentrate on manufacturing technology rather than architecture development. BIT's implementation of the SPARC architecture is an exception here. Although BIT is known for its advances in manufacturing technology, this particular chip was manufactured with 2-μm feature size.

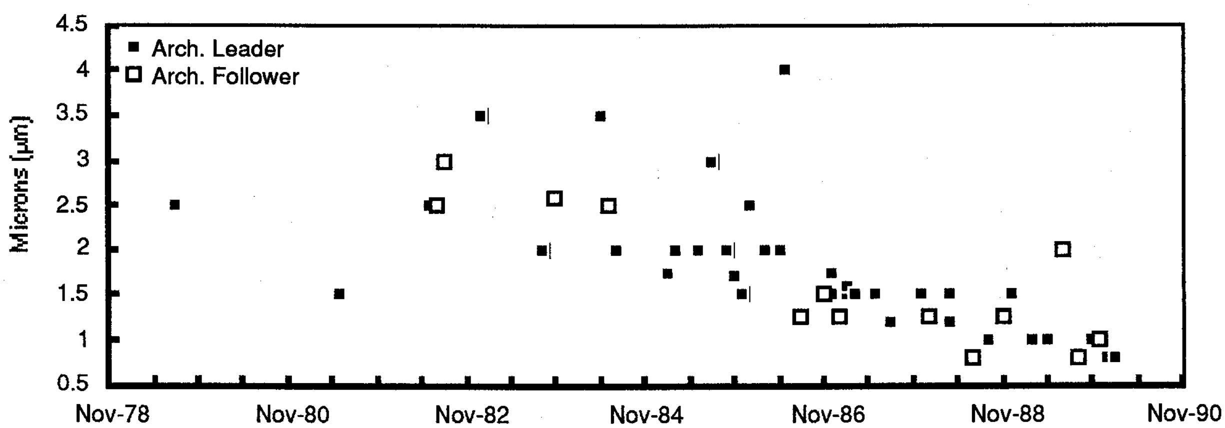

Fig. 25--Microprocessor feature sizes, architecture leaders vs. followers

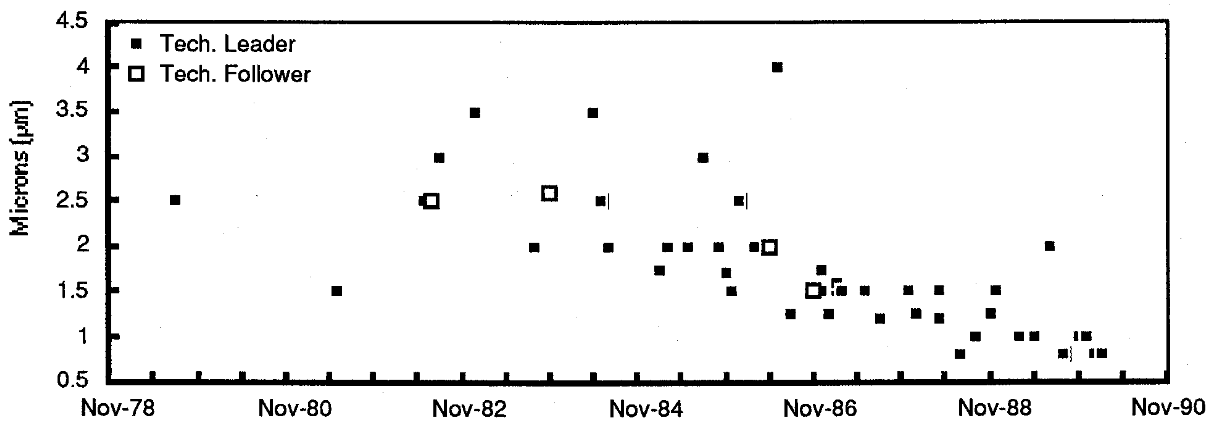

Fig. 26--Microprocessor feature sizes, technology leaders vs. followers

Figure 26 shows features sizes for processors introduced by firms employing technology leader and follower strategies. There are few data points on technology followers, and they are concentrated during the middle of the time period under consideration. Nonetheless, they are not outstanding, either on the high end or on the low end.

Integration Levels

Figure 27 shows integration levels for architecture leaders and followers. Although data are sparse, available points indicate that architecture leaders do not introduce microprocessors with significantly different integration levels than architecture leaders.

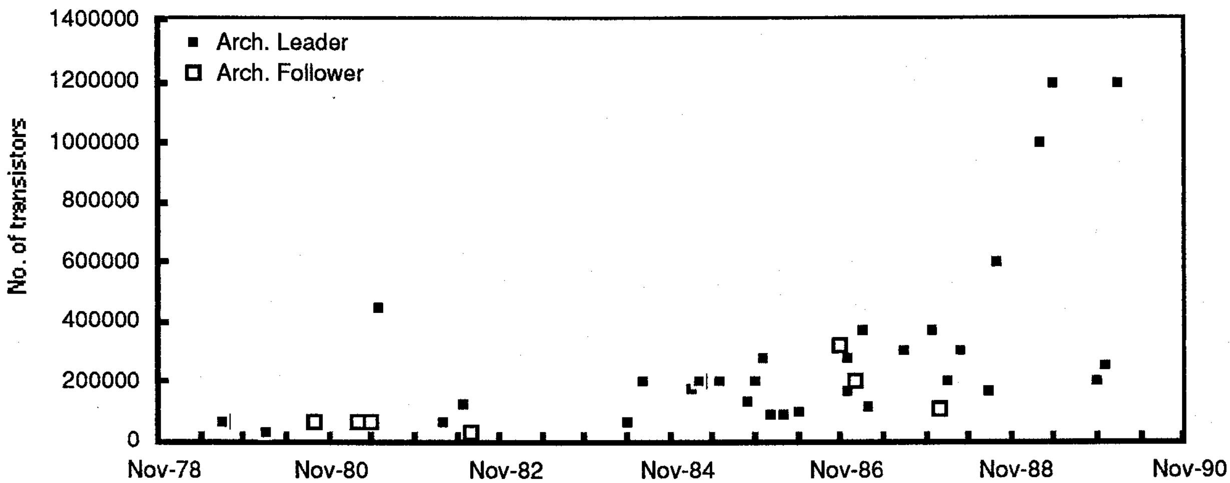

Fig. 27--Microprocessor integration levels, architecture leaders vs. followers

Figure 28 shows integration levels for microprocessors introduced by technology leaders and followers. The available data do not indicate significant differences in integration levels of processors produced by the two types of firms.

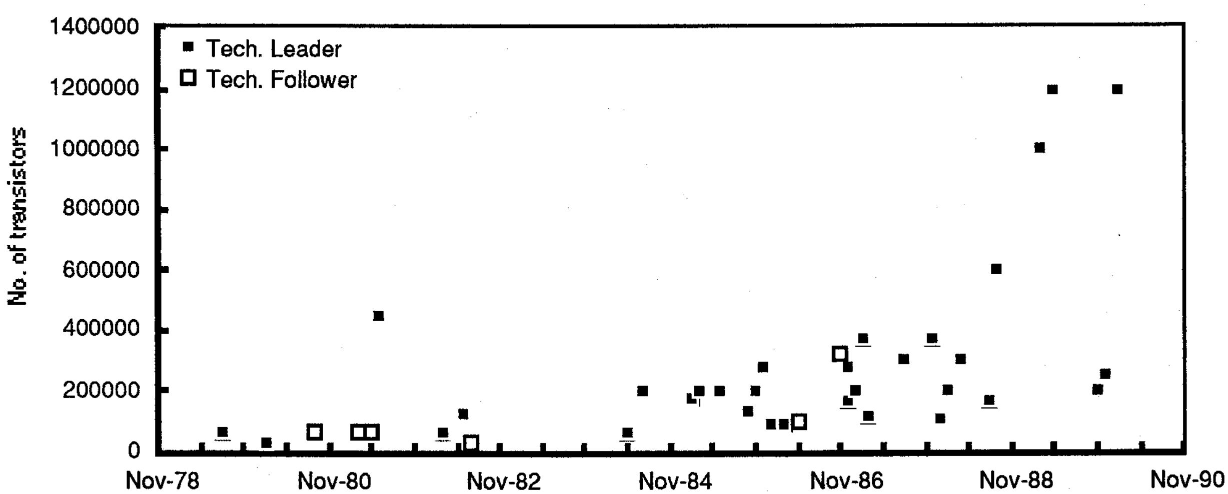

Fig. 28--Microprocessor integration levels, technology leaders vs. followers

Instruction Throughput

Figure 29 shows instruction throughput for microprocessors manufactured by architecture leaders and followers, in millions instructions per second. There seems to be little difference between the processors introduced by the two types of firms. Figure 30 shows the same information for technology leaders and followers, but does not contain sufficient information on technology followers to reach a conclusion about the relative position of the two types of firms with respect to instruction throughput.

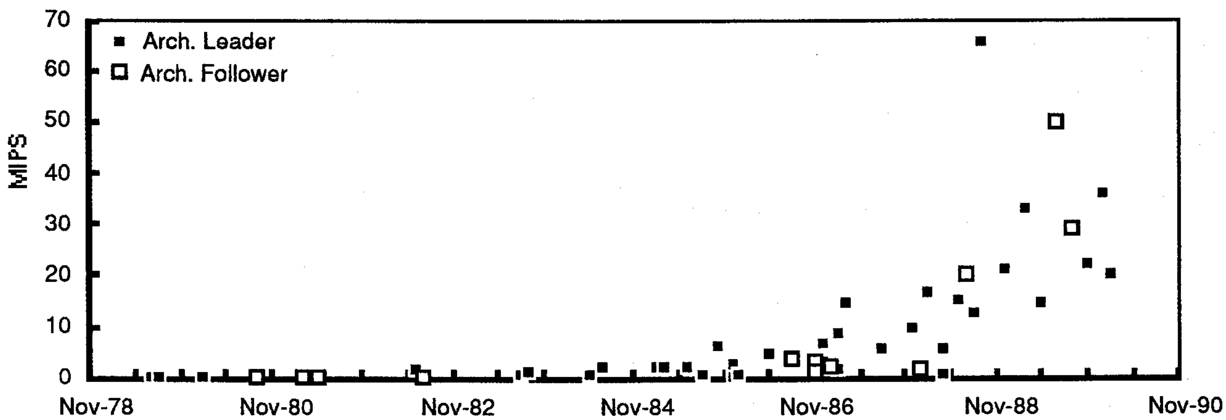

Fig. 29--Microprocessor performance, architecture leaders vs. followers

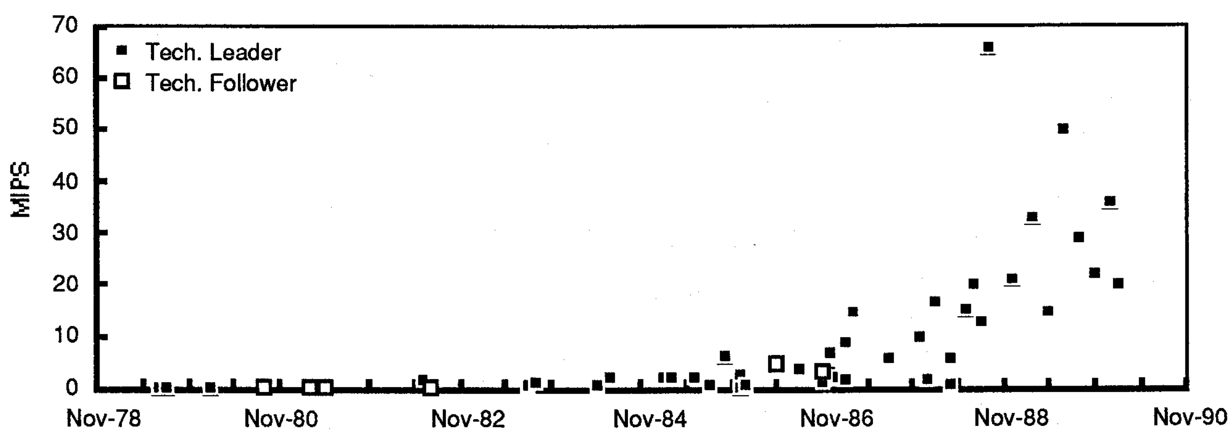

Fig. 30--Microprocessor performance, technology leaders vs. followers

Sampling Price

Firms which license architectures developed by others cannot be automatically presumed to introduce their processors at lower prices than original sources. However, it seems logical to expect lower prices for architecture followers than architecture leaders if there is no shortage of the licensed processors in the market. There is a significant delay involved in second-sourcing, which allows the original source to get a major foothold in the market and to take advantage of learning curves which are so important in the industry. In order to get their products accepted alongside the original source, second sources have to provide incentives, and lower price is one of them.

Figure 31 shows microprocessor prices for architecture leaders and followers at the start of sampling, in constant 1982 dollars. There does not appear to be a great deal of difference between prices for processors introduced by the two types of firms. At least part of the reason for high prices of ICs introduced by architecture followers is accounted for by the fact that all military suppliers of 1750A architecture chips are classified as architecture followers in the data base.

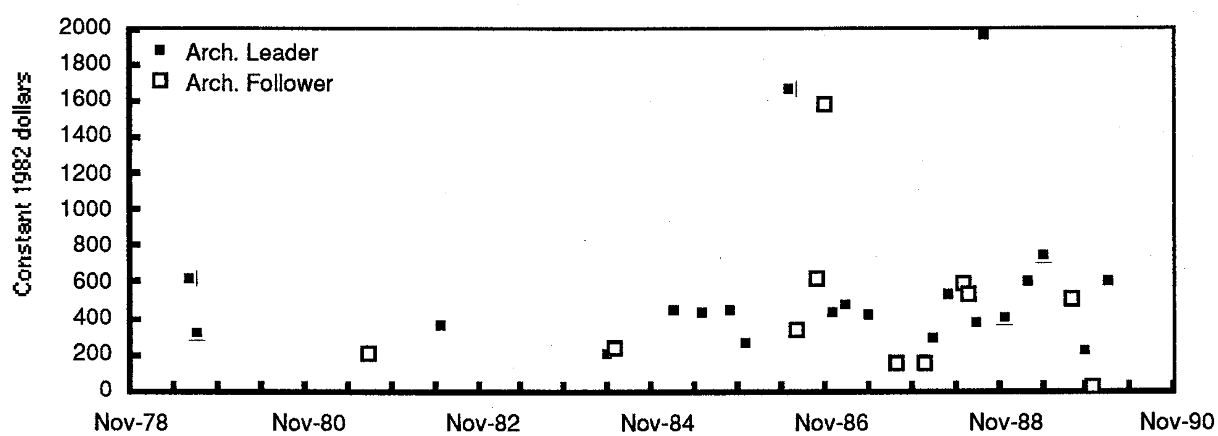

Fig. 31--Microprocessor introductory prices, architecture leaders vs. followers

Figure 32 shows price information from Figure 31, normalized for instruction throughput. There is insufficient information to reach definite conclusions about the differences between microprocessors introduced by architecture leaders and followers, but there do not appear to be significant differences between them.

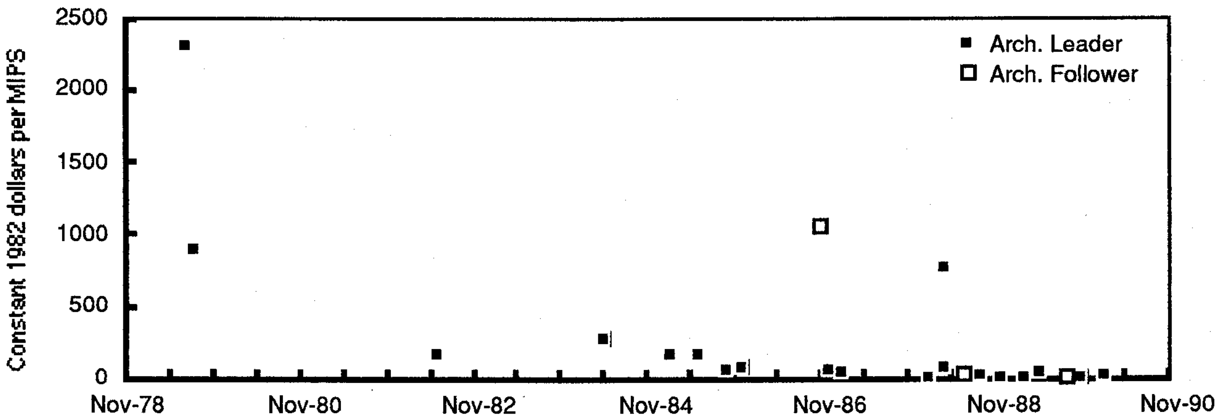

Fig. 32--Microprocessor price/performance ratio, architecture leaders vs. followers

Integrating Multiple Characteristics

Table 4.5 shows results from regression analysis which integrates multiple device characteristics of microprocessors produced by architecture leaders and followers. There is insufficient data on technology leaders and followers to include them in regression analysis. Regressions include several device characteristics, as well as dummies which distinguish architecture followers from leaders, military from commercial processors, and CISC from RISC devices. The architecture follower dummy is not significant in any of the regressions nor in combination with either of the other dummies.

As noted above, architecture followers produce the same processors as architecture leaders, but somewhat later in time. From the regression analysis it appears that the difference in time is not statistically significant.

Table 4.5

REGRESSION RESULTS--MICROPROCESSORS PRODUCED BY ARCHITECTURE LEADERS VS. FOLLOWERS

Variables	Regression 8	Regression 9	Regression 10
Constant	214.155 (0.000)	210.876 (0.000)	216.947 (0.000)
Clock (FI)	0.543 (0.002)	0.569 (0.001)	0.489 (0.010)
Feature Size (FI)	-22.976 (0.000)	-22.149 (0.000)	-22.141 (0.000)
$/MIPS ($82)	- 0.036 (0.000)	- 0.040 (0.000)	- 0.035 (0.000)
Military Dummy		11.442 (0.007)	
CISC Dummy			- 5.208 (0.338)
Arch. Follower Dummy	0.501 (0.897)	- 1.230 (0.744)	1.076 (0.793)
Adjusted R^2	0.780	0.811	0.772

NOTE 1: Numbers in parentheses represent the significance of the coefficient, i.e., 0.010 means that the coefficient is significant at the 1% level.

NOTE 2: "FI" in the variable name means that the data used in the regression was augmented by the technique discussed in Section II.

Hypothesis 4 As It Applies to Microprocessors

The military has bought microprocessors from firms following both leader and follower strategies with regards to architecture. With the exception of the 1750A architecture, designed specifically for military computers, military processors have employed the same architectures as their commercial counterparts. Because common architectures permit the use of already available commercial software "tested" by the market, this approach makes a great deal of sense for the smaller military market.

Fabrication technology is a bit more complicated, though. Technology relevant to non-radiation-hard military circuits generally falls in line with commercial production technology, so entry into the military market can be accomplished by adopting the specific testing requirements of MIL-STD-883B or the much more restrictive MIL-STD-38510. The military could buy non-radiation-hard processors from technology followers, as long as these firms test their circuits to military specifications.

Military contractors which are using the technology leader strategy are generally doing so on the basis of fabrication technology directed specifically at military applications, such as operation in radiation environments. Second-sourcing existing Intel or Motorola architectures is an effective way to get access to the large software bases created for commercial microprocessors and concentrate on technologies of special interest to the military. An example of this is the work done by Harris to create a radiation-hard version of the Intel 8086.

Hypothesis 4 states that the government's preference for funding advanced product R&D precludes it from taking advantage of low-cost circuits created by firms which choose the technology follower strategy. There is no support for this hypothesis in the general-purpose microprocessor market. The majority of effort devoted to R&D by technology leaders in the market has been directed at commercial markets, and the government was a follower almost by necessity. The exception to this is technology for producing radiation-hard circuits. Here, military contractors have led because of lack of commercial interest.

FINDINGS

Let us now summarize the findings about general purpose microprocessors. As discussed in Section II, there are two areas of potential differences between commercial and military products. Different ICs may be necessary in commercial and military applications because the functions they perform are different. This is not the case for microprocessors, as can be seen from the fact that many of the same processors (albeit not always produced by the same firms and in the same implementation) appear as both commercial and military processors. Both military and commercial microprocessors are used for data processing and embedded control. Both sets of microprocessors perform the functions described in Appendix B. Both sets of processors use the same architectures.[15] Both commercial and military customers want greater processing capacity and faster speeds at lower prices. It is, therefore, possible that advances in microprocessor performance, either through advances in fabrication technology or through the development of improved architectures, could have come about in either commercial or military markets. In fact, commercial markets dominated in technology advances, except in the area of rad-hard technology. Even RISC, funded by the DoD, succeeded in commercial markets before its acceptance by the military.

The second possibility that accounts for differences in commercial and military microprocessors is that environments in which they must operate are different. Such differences do, in fact, exist. Military chips must operate within a wider temperature range, and the relative difference in temperature specifications has not changed over time. However, commercial firms have an interest in improved temperature performance because ability to deal with hostile environments permits the ICs to serve in a greater

[15]The DoD-defined 1750A architecture found its way into the commercial market via the commercial communications satellites--1750As in SOS are being used on both commercial and military satellites.

variety of applications. The fact that the chips for both markets are often produced on the same lines and are simply tested differently[16] is an indication that commercial manufacturers made significant progress in this area without necessarily having the military market in mind.

Radiation tolerance is much more relevant to the military, and we would expect the advances related to it to appear in military rather than commercial markets. Some improvements in radiation tolerance of commercial processors were achieved as a result of going to technologies which are inherently more rad-hard, but these improvements were serendipitous. There have not been many studies of radiation tolerance done on commercial components because such studies are expensive and not usually considered necessary. However, there are indications that a current-generation commercial microprocessor might have radiation tolerance of less than 10^4 rads total dose, a factor of 100 or more less than circuits designed specifically for radiation tolerance, with current technology. This makes commercial microprocessors unsuitable for those applications in which high radiation tolerance is required.[17] In fact, microprocessors used for commercial communication satellites are those used for military rad-hard applications because military radiation tolerance specifications are much closer than commercial specifications to the environment faced by space-based equipment.[18] Since data on radiation tolerance of commercial circuits are not easily available, one of the areas where some DoD investment would we worthwhile is measurement of radiation tolerance of commercial microprocessors. Such information would be useful in view of the trends toward more radiation tolerant technologies in commercial microprocessors.

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[16]Interviews.

[17]Firm interviews.

[18]I am referring here to satellites which are placed in high orbit and remain in place for long periods of time, such as geosynchronous communication satellites. Not all equipment which operates in space faces the same radiation requirements. Electronic equipment on the Space Shuttle, for example, which operates for short times in close earth orbit, faces a much milder environment.

V. DIGITAL SIGNAL PROCESSORS

A digital signal processor (DSP) is a system or device that accepts digitized signal information, performs some mathematical operations on the information, and then delivers the result to a host system or peripheral.[1] Major applications of DSPs include radar, sonar, navigation, guidance, speech recognition, and image processing. Digital signal processing is preferred to analog processing (despite the fact that the world is analog and the information about the world is usually collected by analog sensors) because digital signal processors have higher reliability, insensitivity to temperature changes and greater tolerances, accuracy, repeatability, and flexibility. General purpose microprocessors can execute digital signal processing tasks, but they are much too slow for real-time applications. DSPs are stripped down to optimize performance of repetitive mathematical operations with large data throughputs. While a general purpose microprocessor performs multiplications in a series of additions and shifts, requiring dozens of machine cycles, a DSP multiplies different bits of a number in parallel, requiring only a single machine cycle for a multiply-accumulate operation central to digital filtering.

The processing block of the digital signal processing system is comprised of an arithmetic logic unit (ALU), a multiplier-accumulator, a controller and sequencer, and data, coefficient, and instruction memories. Although these functions started out on separate chips, they have been migrating onto a single chip as improvements in fabrication technology permit greater integration levels. Although a single-chip DSP usually relies on off-chip program and data memories, other parts of DSP systems are now found on-chip. Performance of digital signal processing systems can often be improved by linking together (cascading) several DSP ICs, which increases the degree of parallel operation.

A digital signal processing system can be based either on a general-purpose single-chip DSP or on a chip set of function-specific "building block" ICs. Single-chip DSPs implement digital signal-processing algorithms in software, while function-specific ICs implement these algorithms in hardware. Single-chip DSPs are less expensive and take up less board space than combinations of building block components, but they are not as fast. They also require considerably more programming effort than building-block

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[1]The definition is taken from "Coming To Terms with Digital Signal Processing," *Electronic Design*, May 17, 1984, p. 104.

systems. Systems built with building-block components require little software, but offer only specific functions. Systems designers must trade off these factors during design. While single-chip general-purpose DSPs are most often used in lower-performance high-volume systems, building-block ICs are used for high-performance applications.

Both single-chip and building-block DSPs can be fixed-point (i.e., operating on integers only) or floating-point. Floating-point ICs have a very large dynamic range which allows for accurate representation of very small numbers, so there is no concern about overflow or rounding errors during calculations. This is particularly useful for single-chip DSPs because it allows designers to ignore the nature of the data on which the IC will operate. On the other hand, fixed-point DSPs can be faster in some applications because they do not need to operate on both a mantissa and an exponent.

Early DSPs were 8-bit devices. For the majority of signal-processing applications which deal with natural phenomena, 16-bit fixed-point devices provide an adequate dynamic range, but users have to be careful about rounding errors or numeric overflow in intermediate calculations. To avoid errors, intermediate calculations must be checked and scaled, which takes execution time, and slows down the calculation. For this reason, 24-bit and 32-bit DSPs are most popular. These DSPs are also useful for dealing with synthetic objects in applications such as graphics processing. Floating-point devices provide an essentially infinite dynamic range and are used for scientific number crunching.

Several benchmarks are used to measure the speed of digital signal processors:

1. instruction cycle time
2. million operations per second (MOPS)
3. million adds per second (MADS)
4. million multiplies per second (MMPS)
5. time to perform FIR filtering
6. time to perform fast Fourier transform (FFT)
7. time to perform a multiply-accumulate operation.

In order to compare as wide a range of DSPs as possible, this study looks only at two benchmarks: the instruction cycle time and throughput in millions of operations per second (MOPS). These are very general and do not represent the full capabilities of DSPs under analysis, although they do give an idea about speed--the major attraction of DSPs. Several factors have contributed to increases in speed over time. One of these has been greater levels of integration. Another has been a variety of improved architectures that have contributed to increases in speed.

CLASSIFYING FIRMS

Table 5.1 shows firms which are included in the DSP data base, together with their classification in accordance with the taxonomy developed in Section II.

Unlike other components discussed in this study, digital signal processor development has been significantly influenced by systems-oriented firms. Although most of the market share has been held by Texas Instruments,[2] a component-oriented firm, AT&T, IBM, and others have developed and used their own DSP devices which focused on the needs of their own systems and end-use markets.

In addition to large firms, several smaller firms have participated in the market and made substantial contributions. Analog Devices entered the DSP market from a position of strength in analog signal processing devices and analog-to-digital converters. It has since developed a number of advance single- and multi-chip DSPs. Zoran Corp., a Silicon Valley start-up, introduced substantial speed increases into single-chip DSPs by introducing vector processing into the general-purpose DSP market.

The military has been very interested in DSP throughout the history of signal processing, and has played an important role in the development of DSP. DSP building block components were particularly emphasized during the VHSIC Program. Of the firms represented in the table, Honeywell, IBM, Motorola, National Semiconductor, Texas Instruments, and TRW participated. VHSIC Phase 1 chips, demonstrated in 1985, were more advanced than any commercial DSP ICs on the market at the time, mostly in high-performance building block components, emphasized by the military. In addition to the speed enhancements expected from improvements in manufacturing technology, several new algorithms were developed as part of the VHSIC Program.

PRODUCT EVALUATION

The data base used for this study includes single-chip and multi-chip DSPs. It does not include individual building-block components, such as multipliers or filters, because there is no way to compare them on a common basis. This limits the extent to which the DSP market can be described because individual building-block components are very fast and used in many high-end applications. The biggest problem with limiting

[2]According to Forward Concepts, a market research group, Texas Instruments had 63% of the DSP market in 1989. Quoted in J. Mosley, "Who's Who In DSP?" *Electronics World + Wireless World*, May 1990, p. 413.

the market in this way is that it excludes many advanced DSP ICs used by the military, which has relied mostly on building-block components.

Table 5.1

CLASSIFICATION OF DSP PRODUCERS

Firm Name	Commercial or Military	Systems or Components	Leader or Follower
AMD	C	Co	L
Analog Devices	C, M	Co	L
AT&T	C	S	L
BIT	C	Co	L
Fujitsu	C	Co	L
General Instr.	C	S	F
Gould AMI	C	S	L
Hitachi	C	Co	L
Honeywell	C, M	S	L
IBM	M	S	L
Inmos	C	Co	L
ITT	C	S	L
Microchip Tech.	C	Co	F
Motorola	C, M	Co	L
National Semi.	C, M	Co	L
NCR	C	S	L
NEC	C	Co	L
Oki	C	Co	L
Philips	C	S	L
Plessey	C	Co	L
Raytheon	M	S	L
Texas Instruments	C, M	Co	L
Thomson	C	S	L
TRW	M	S	L
UTMC	M	S	L
Weitek	C	Co	L
Zoran	C	Co	L

Commercial applications of DSP did not really come to the fore until the mid-1980s, and the commercial DSP market has grown rapidly since that time. Software compatibility has traditionally been less of concern to DSP manufacturers and users than to users of general-purpose microprocessors. The Institute of Electrical and Electronic Engineering (IEEE) had developed a standard for the representation of floating-point numbers, and most DSP manufacturers comply with this standard, although several manufacturers use their own standard.

The first DSP is sometimes considered to be Intel's 2920, introduced in the late 1970s. However, it was slow and never very popular. In 1980, the first single-chip DSP

with a dedicated hardware multiply-accumulator, μPD7720, was released by NEC. Shortly after that, Intel left the DSP market entirely. In 1982, Texas Instruments introduced its TMS320 series which quickly became industry standard, and is still leading both commercial and military markets for single-chip DSPs.

The first member of the TMS320 family was the TMS32010, a contemporary of the Intel 8088. Like that early microprocessor, the 32010 is now obsolete for those applications in which it was originally successful, but is still in use for embedded control applications. The second member of the family, the TMS32020, offered more on-chip functions and greater speed than the 32010. Its successor, the TMS32025, is still widely used, having now migrated from NMOS to CMOS.

In 1986, Analog Devices introduced its 16-bit DSP, ADSP2100. The device is a very fast fixed-point processor, which can be used as a fast co-processor with a Motorola 68000-series chip.

The latest member of the TMS320 family is the TMS32030, a 32-bit floating-point device introduced in 1988. It is very fast and highly integrated. However, its floating-point representation is unique to TI, making the device incompatible with DSPs from other manufacturers.

AT&T also has a set of DSP ICs. Not surprisingly, the emphasis and widest use of these ICs is in the communication market. AT&T's first DSP, DSP32, was released in 1986. It was the same IC used by AT&T in its own communications hardware, and was the first 32-bit floating-point DSP with wide market release.

Zoran's first vector signal processor (VSP) entered the market in 1986, using software improvements to significantly improve speed, although the IC was implemented in conservative 2-μm technology.

Motorola entered the DSP market late. Its first device, the 24-bit fixed-point DSP56000, was introduced in 1987. Because of late entry and a decision not to remain compatible with old architectures, the 56000 was designed with advanced features, such as 24-bit data width and 56-bit multiply/accumulate units which protect from overflow and minimize checking and scaling. The chip's instruction set drew heavily on the architecture of the Motorola 680X0 family of microprocessors.

Motorola's second DSP family, the 96000 series, is a 32-bit floating-point family with an instruction set which is a superset of the 56000 instruction set. The first device in the series was introduced in 1988. In addition to being a floating-point device, it corrects some of the weaknesses of the 56000 family. Its use of standard representation for floating-point numbers allows the 96000 to be used as a powerful co-processor with

standard microprocessors, such as the 68040 or Intel's 80486. In addition to its other features, the 96000 included a circuit emulator on-chip, which allows for testing of the DSP itself, as well as providing checks on other parts of the system.

With the general overview in place, let us now look at individual device characteristics for DSPs.

Commercial vs. Military

The first comparison to be made in accordance with the taxonomy developed in Section II is that between commercial and military DSPs. A comparison will be made for five characteristics: cycle time, operation throughput (in millions of operations per second), IC feature size, power dissipation, and introductory prices at the time of sampling.

Cycle Time

Figure 33 shows a comparison of instruction cycle times for commercial and military DSPs. As can be expected from the improvements in manufacturing technologies and architectures, the general trend has been downward. Although there are comparatively few data points for military DSPs, these seem to be distributed throughout the range. The military points do not appear to be significant outliers, although they generally appear to the right of comparable commercial points, i.e., later in time.

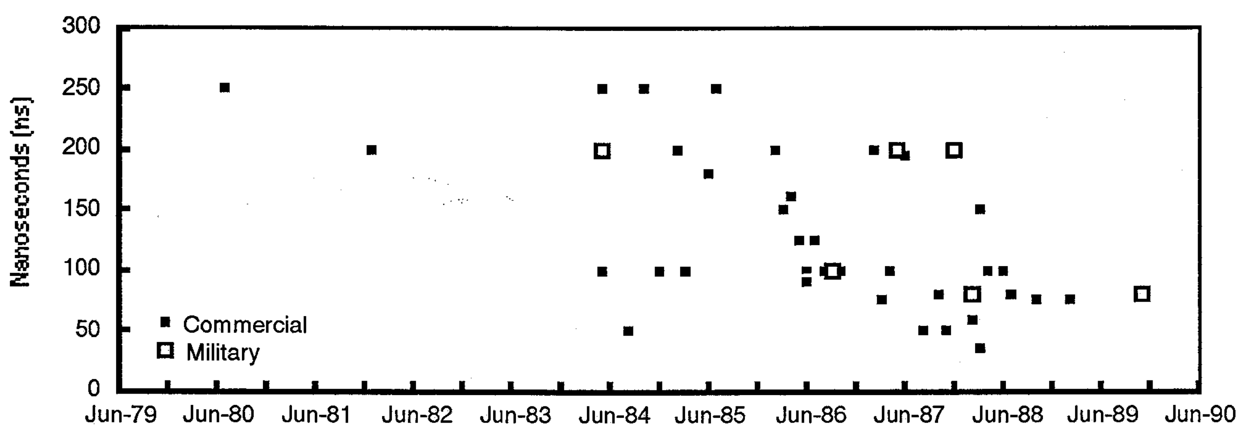

Fig. 33--DSP cycle times, commercial vs. military

Throughput

DSP throughput is shown in Figures 34 and 35. Figure 35 shows lower-performance ICs which are crowded against the horizontal axis in Figure 34. In both figures, military DSPs appear as high-performers along this dimension. In fact, almost all the high-end outliers are military ICs.

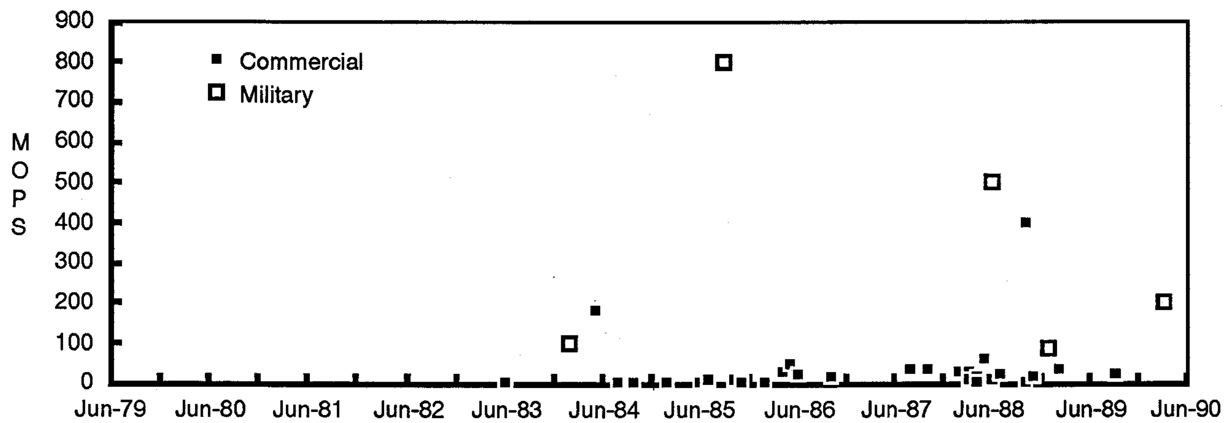

Fig. 34--DSP throughput, commercial vs. military

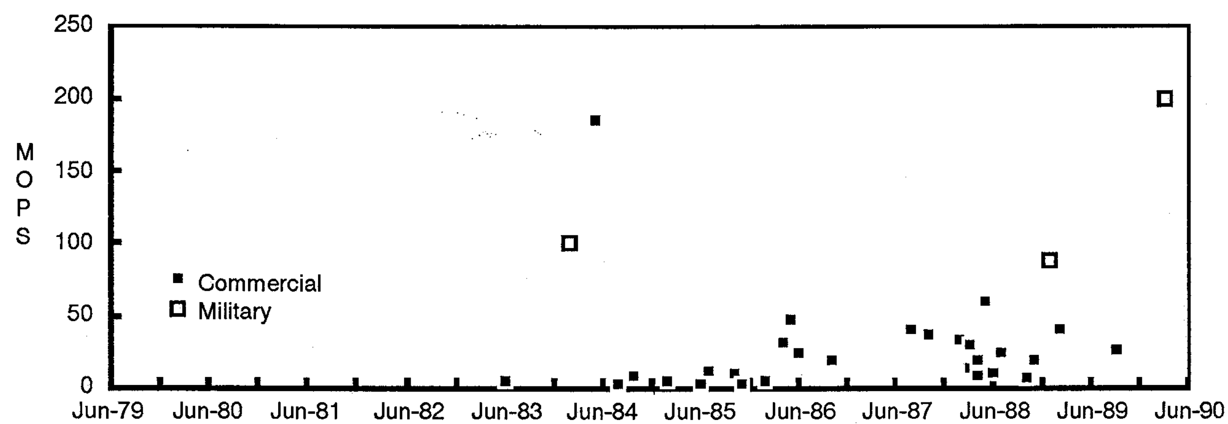

Fig. 35--DSP throughput, lower-performance ICs, commercial vs. military

Feature Sizes

Feature sizes employed in IC fabrication are shown in Figure 36. Military ICs show a clear lead during 1983, when they were fabricated with 1.25-μm technology vs. approximately 2-μm technology used in commercial markets. It is interesting to observe that the next significant advance in military feature sizes came with the introduction of the CPUAX after the completion of VHSIC Phase 2. During that time, commercial feature sizes have fallen to about 0.8 μm in a smooth progression.

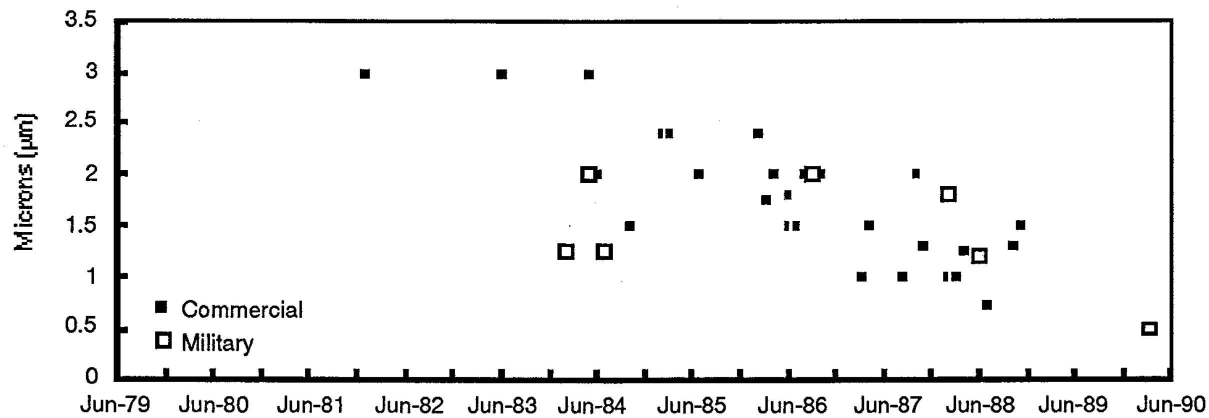

Fig. 36--DSP feature sizes, commercial vs. military

Power Dissipation

Since speed is the key parameter for DSPs, and bipolar ICs are inherently faster than MOS ICs, bipolar technology was the manufacturers' choice for producing these ICs. With bipolar or NMOS processing, however, power consumption levels rose to several watts. To cut power dissipation, CMOS has become the processing technology of choice as greater integration levels have permitted speed to rise. Power dissipation levels for commercial and military DSPs are shown in Figure 37.

There does not appear to be very much difference between the commercial and military ICs shown. The clear outlier, with power dissipation of 17 watts, is the TRW/Motorola CPUAX, developed under Phase 2 of the VHSIC Program. However, the chip, composed of over 4 million transistors, is also very large compared to other ICs, so it is not surprising that its power dissipation is high.

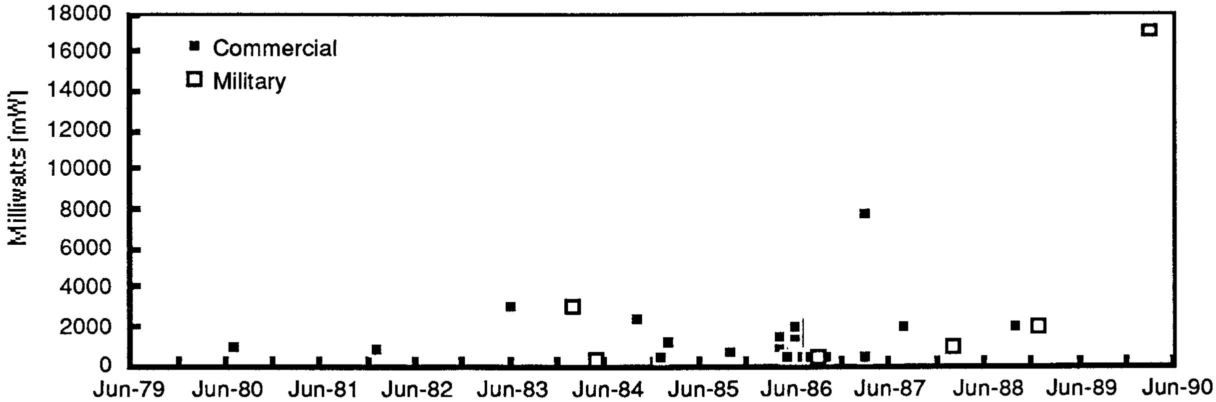

Fig. 37--DSP power dissipation, commercial vs. military

Introductory Prices

Figure 38 shows the introductory prices for commercial and military DSPs. Although the data on military DSPs are limited, the more recent ICs appear to be higher priced than their commercial counterparts. However, as noted above, they were also high-performance ICs which might account for the difference. The ratio of price to throughput is shown in Figure 39.

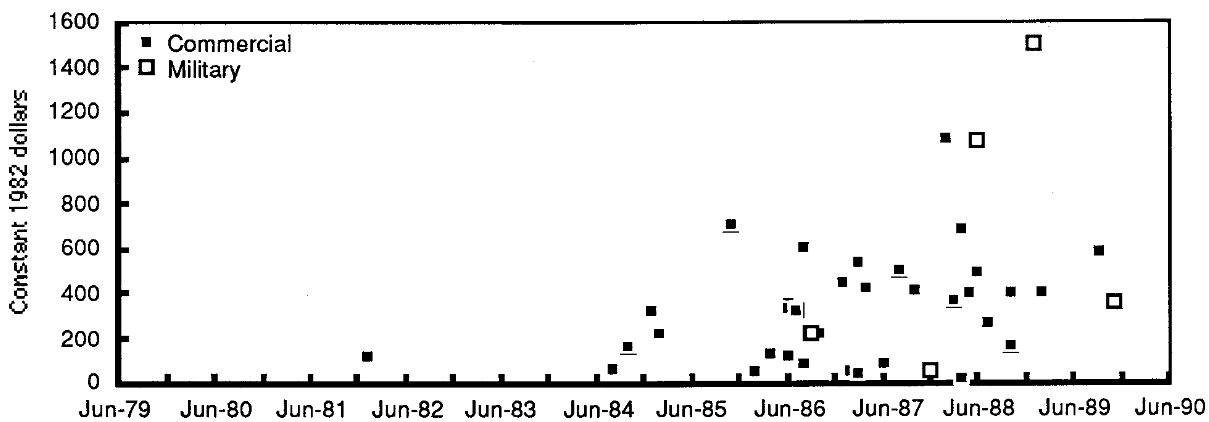

Fig. 38--DSP introductory prices, commercial vs. military

There are few observations in the data base in which both throughput and introductory price are known for military ICs. However, from the available data points military ICs do not appear to be outliers on price when performance is taken into account.

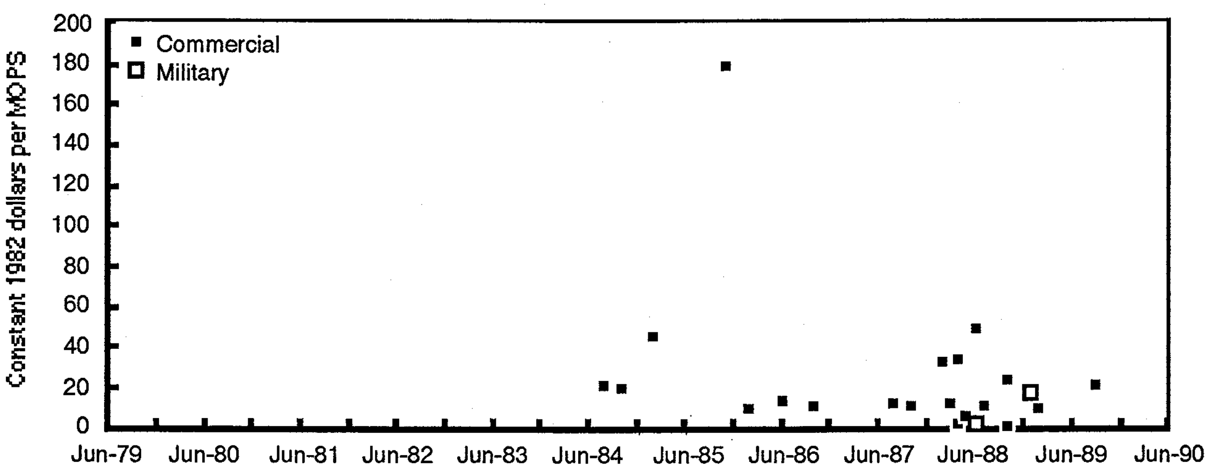

Fig. 39--DSP price-performance ratio ($/MOPS), commercial vs. military

Integrating Multiple Characteristics

In the description of different IC characteristics, it appeared that military DSPs led along some dimensions, but lagged along others. In order to determine whether commercial and military producers of DSPs made different trade-offs in their ICs, a multivariate regression analysis was performed. Results of this analysis are shown in Table 5.2.

As can be seen from regression 1, the fit to the data is quite good without any of the dummy variables. The variables which are included in the regression have expected signs: negative for "Cycle Time" (i.e., faster ICs are introduced later); negative for "Feature Size"; positive for "Power Dissipation," which is not particularly surprising in view of the growth in IC sizes and integration levels; and negative for "$/MOPS." When a military dummy is added to the regression, it is not significant, and does not contribute any information to the regression, as noted by the Adjusted R^2. In fact, the dummy that improves fit is the systems dummy, and the fact that many of the systems firms in the data base also have a presence in military markets is the probable explanation in this case.

Table 5.2

REGRESSION RESULTS--COMMERCIAL VS. MILITARY DSPS

Variables	Regression 1	Regression 2	Regression 3
Constant	185.526 (0.000)	186.149 (0.000)	187.562 (0.000)
Cycle Time (FI)	- 0.099 (0.002)	- 0.094 (0.004)	- 0.081 (0.010)
Feature Size (FI)	- 21.937 (0.000)	- 22.471 (0.000)	- 23.062 (0.000)
Power Dissipation (FI)	0.001 (0.070)	0.001 (0.062)	0.001 (0.053)
$/MOPS (FI)	- 0.186 (0.005)	- 0.186 (0.005)	- 0.198 (0.002)
Military Dummy		- 2.878 (0.418)	- 1.192 (0.734)
Systems Dummy			- 6.764 (0.027)
Adjusted R^2	0.794	0.793	0.806

NOTE 1: Numbers in parentheses represent the significance of the coefficient, i.e., 0.010 means that the coefficient is significant at the 1% level.

NOTE 2: "FI" in the variable name means that the data used in the regression was augmented by the technique discussed in Section II.

Hypothesis 1 As It Applies to DSPs

Hypothesis 1 stated that commercial markets can be expected to be on par with or lead military markets in technology. The data do not support this hypothesis in DSP markets, even without the presence of high-performance building-block ICs which have been used by the military to a greater extent than single-chip DSPs. Military ICs lead in throughput, a performance characteristic which is probably more important to the users than many other characteristics of DSPs. Although military DSPs are more expensive, in the few cases where both throughput and price are available, military DSPs do not stand out from their commercial counterparts in the price/performance ratio.

Although military DSPs lag along dimensions other than throughput, the difference between commercial and military parts is not large. This is not encouraging for the future of the military lead, given the fact that DSPs are becoming increasingly important in commercial markets.

Generation Skipping

There is no indication that DSPs have skipped generations. The only DSP that can be considered to have done so is the CPUAX produced under Phase 2 of the VHSIC Program. Although this DSP is larger, more complex, and possesses more advanced features than any other DSP, it is still an experimental device and is not included in either military or commercial systems. Depending on when this DSP is available for incorporation in systems, and on the state of DSP technology at the time, the judgement

can be made on whether it constitutes a generational advance over other ICs on the market. At the moment, Hypothesis 2 is supported by the data.

Systems- vs. Component-Oriented Firms

As noted above, systems-oriented firms have played a significant role in the DSP market. The differences in IC characteristics of DSPs introduced by systems- and component-oriented firms are presented below.

Cycle Time

Cycle times for systems- and component-oriented firms are shown in Figure 40. Systems firms appear throughout the range, both to the left and to the right of comparable component-oriented data points, and both above and below. There does not appear to be a difference along this dimension.

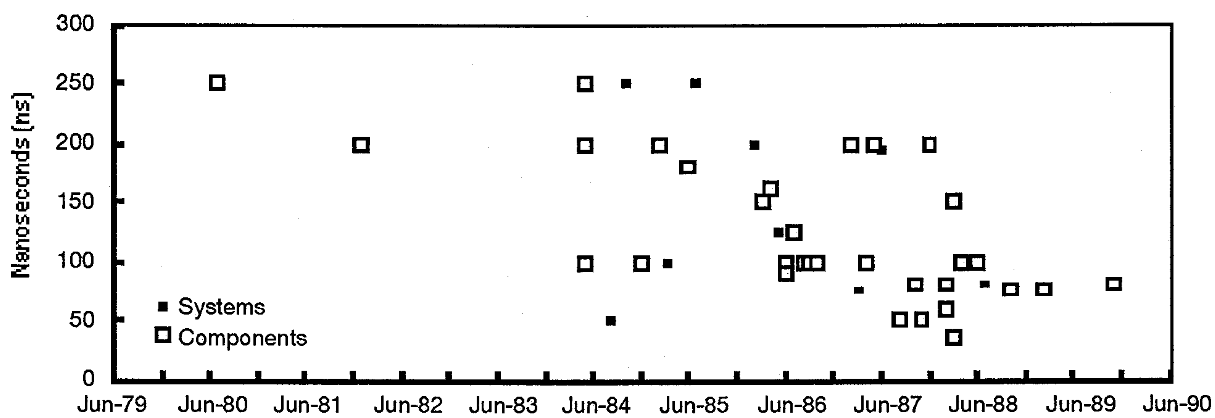

Fig. 40--DSP cycle times, systems- vs. component-oriented firms

Throughput

Throughput for systems- and component-oriented firms is shown in Figures 41 and 42. Both figures show that DSPs from systems-oriented firms have generally higher throughputs than those manufactured by component-oriented firms. Since there does not appear to be much difference between cycle times in DSPs produced by systems- and component-oriented firms, other factors must be responsible for the advantage in throughput exhibited by these ICs.

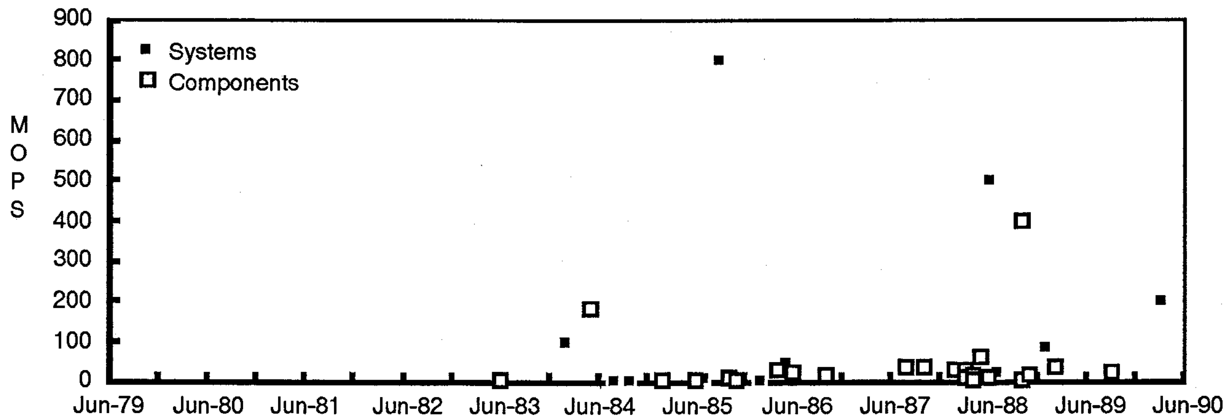

Fig. 41--DSP throughput, systems- vs. component-oriented firms

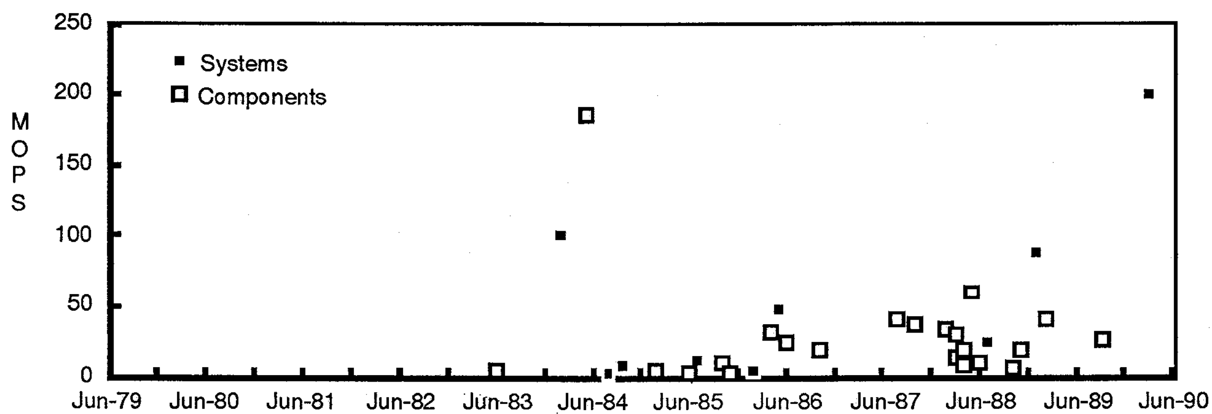

Fig. 42--DSP throughput, lower-performance ICs, systems- vs. component-oriented firms

Feature Sizes

Feature sizes are shown in Figure 43. Systems firms have the advantage over component-oriented firms along this dimension. Although some data points appear to be

retrogressive, all the low data points and the points which appear on the left (i.e., earliest in time) are points corresponding to DSPs produced by systems-oriented firms.

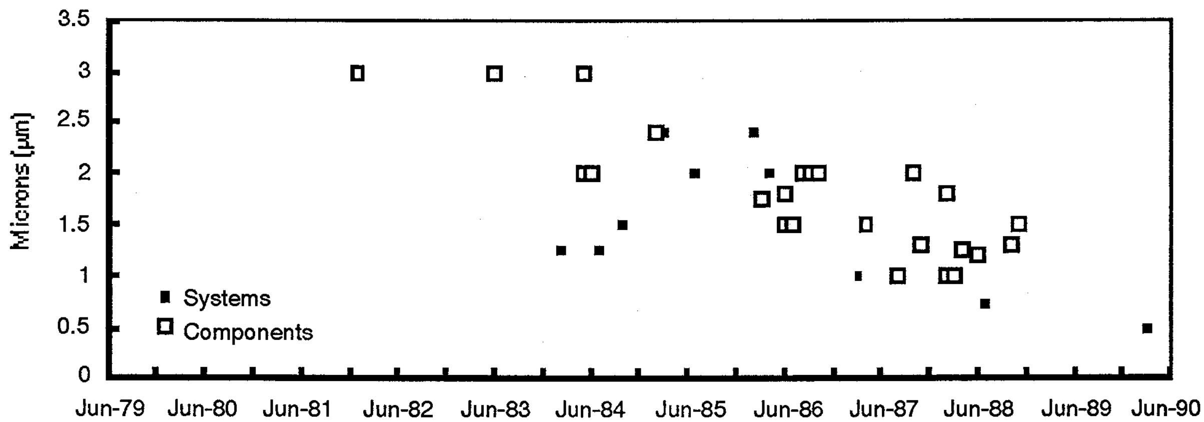

Fig. 43--DSP feature sizes, systems- vs. component-oriented firms

Power Dissipation

DSP power dissipation is shown in Figure 44. Generally, systems firms produce ICs with higher power dissipation than component-oriented firms. The most significant outlier, of course, is the TRW CPUAX, the large military processor fabricated under Phase 2 of the VHSIC Program.

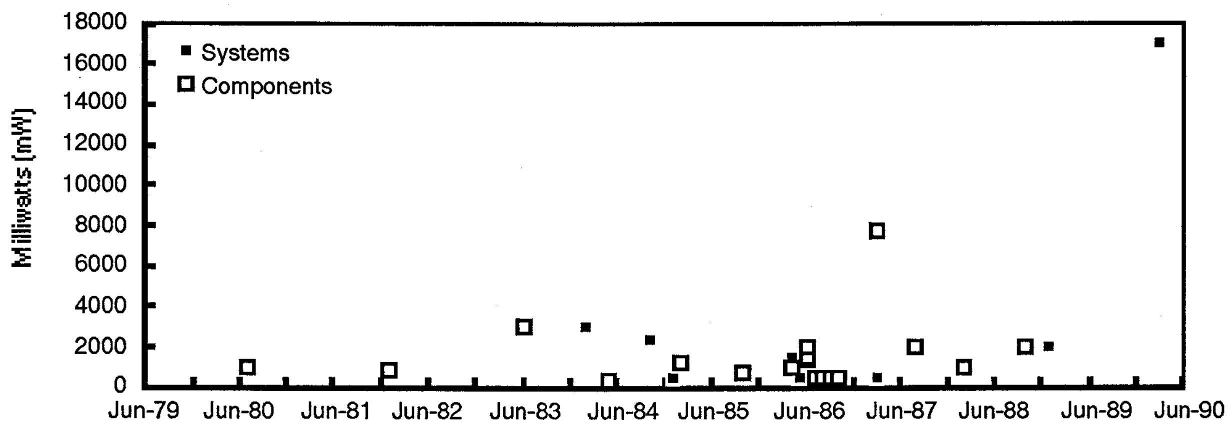

Fig. 44--DSP power dissipation, systems- vs. component-oriented firms

Introductory Prices

Although they generally turn in higher performance, DSPs produced by systems-oriented firms are not generally introduced at higher prices, as shown in Figure 45. In fact, when performance is taken into account, DSPs introduced by systems-oriented firms are lower-priced than those introduced by component-oriented firms, as presented in Figure 46.

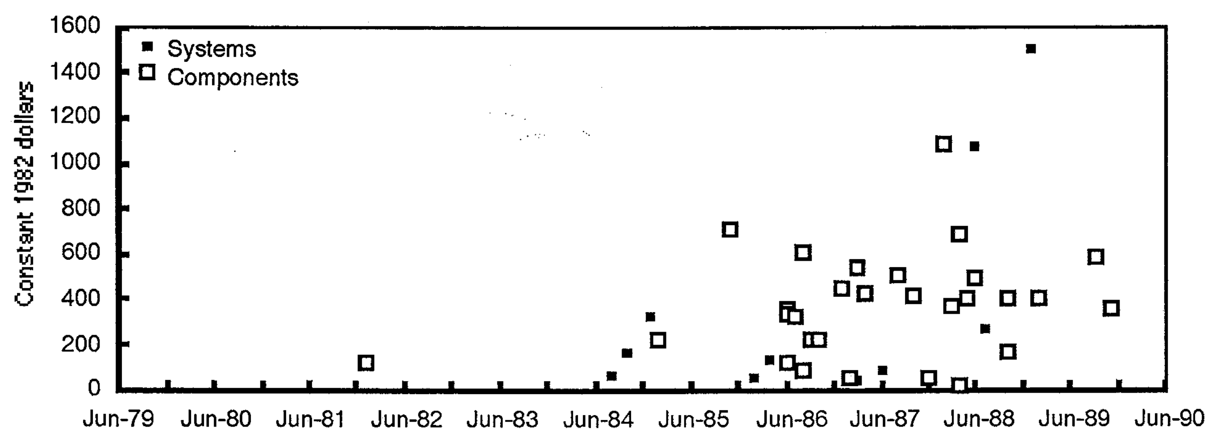

Fig. 45--DSP introductory prices, systems- vs. component-oriented firms

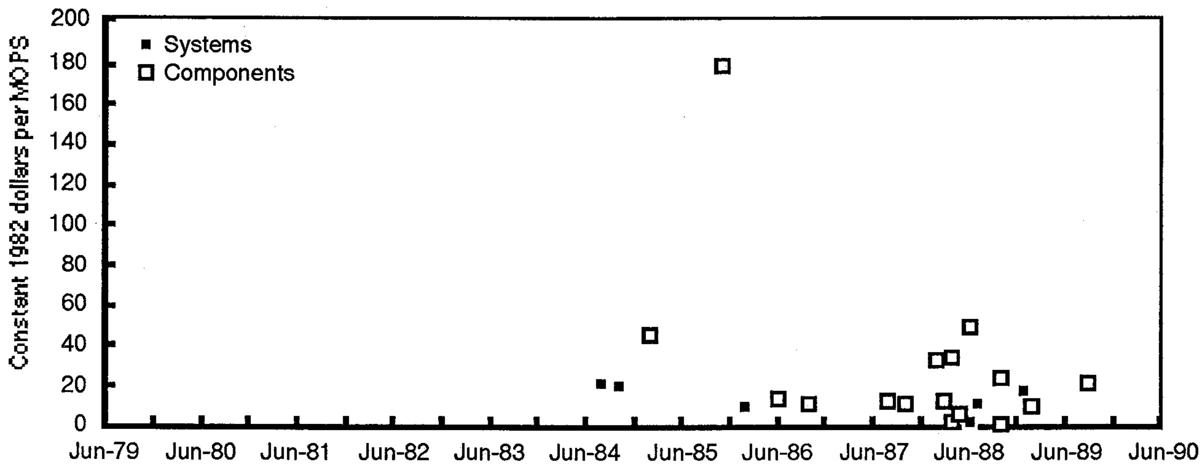

Fig. 46--DSP price/performance ratio, systems- vs. component-oriented firms

Integrating Multiple Characteristics

Multivariate regression analysis of DSPs for systems- and component-oriented firms is presented in Table 5.3. As noted above, systems firms have played an important part in the DSP market, and this is reflected in the sign and size of the coefficient for the systems dummy in the regressions.

Table 5.3

REGRESSION RESULTS--DSPS PRODUCED BY SYSTEMS- VS. COMPONENT-ORIENTED FIRMS

Variables	Regression 4	Regression 5
Constant	187.361 (0.000)	195.080 (0.000)
Cycle Time (FI)	- 0.083 (0.008)	- 0.081 (0.010)
Feature Size (FI)	- 22.870 (0.000)	- 25.621 (0.000)
Power Dissipation (FI)	0.001 (0.053)	
$/MOPS (FI)	- 0.198 (0.002)	- 0.207 (0.002)
Military Dummy		
Systems Dummy	- 6.980 (0.019)	- 6.850 (0.024)
Adjusted R^2	0.809	0.800

NOTE 1: Numbers in parentheses represent the significance of the coefficient.
NOTE 2: “FI” in the variable name means that the data used in the regression was augmented by the technique discussed in Section II.

The variables presented in regressions 4 and 5 are the same as those presented in regressions 1 through 3 in Table 5.2, with the exception of the military dummy. The negative sign of the systems dummy and its significance in the regression mean that systems firms enter the market earlier than component-oriented firms with DSPs of similar characteristics.

Hypothesis 3 As It Applies to DSPs

Hypothesis 3 stated that component-oriented firms may be expected to lead their systems-oriented counterparts in introducing advanced components. Not only is this not borne out by the data, but both the individual component analysis and multivariate regression analysis show that DSPs produced by systems-oriented firms are introduced before DSPs of similar characteristics introduced by component-oriented firms.

Leaders vs. Followers

As noted in Table 2.4, the information available about firms using the follower strategy in the DSP market is limited. The figures presented below are used for speculation rather than analysis. No integrative regression analysis was performed.

Cycle Time

Cycle times for DSPs manufactured by leaders and followers are shown in Figure 47. DSPs manufactured by technology followers have longer cycle times than those manufactured by technology leaders.

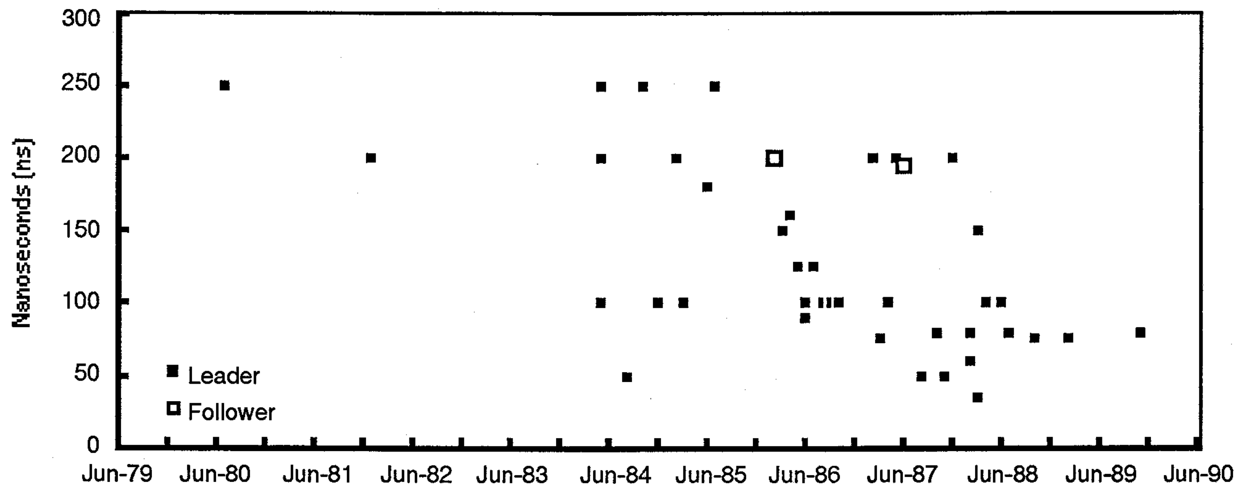

Fig. 47--DSP cycle times, leaders vs. followers

Throughput

DSP throughput is shown in Figures 48 and 49. As might be expected, the DSPs manufactured by followers have lower throughputs than those manufactured by leaders.

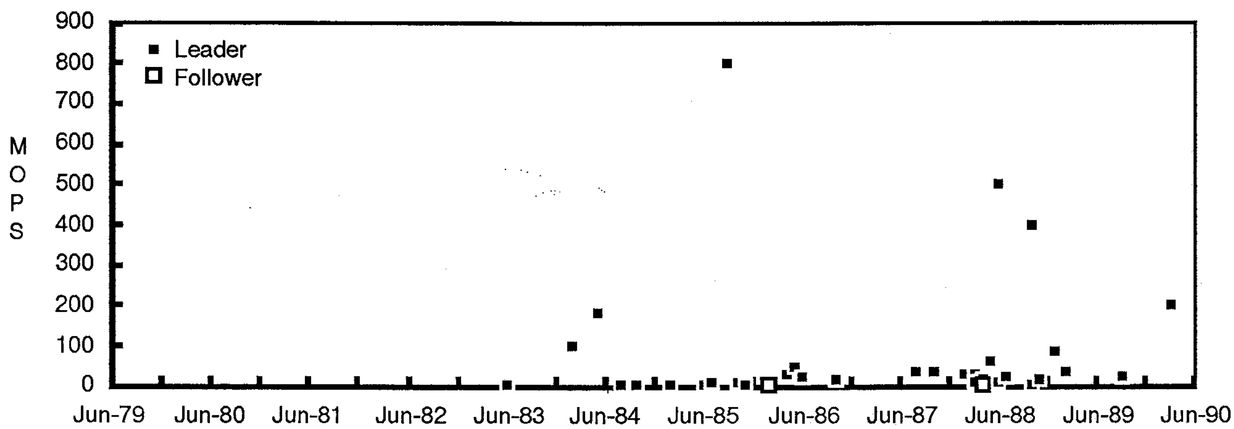

Fig. 48--DSP throughput, leaders vs. followers

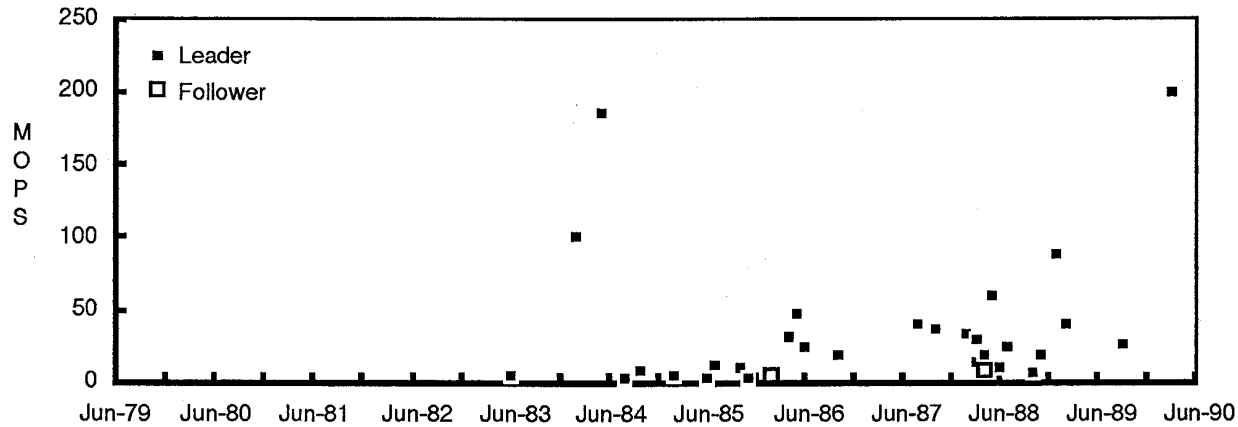

Fig. 49--DSP throughputs, lower-performance ICs, leaders vs. followers

Feature Sizes

There is essentially no information on feature sizes of technology followers. All the available information is shown in Figure 50.

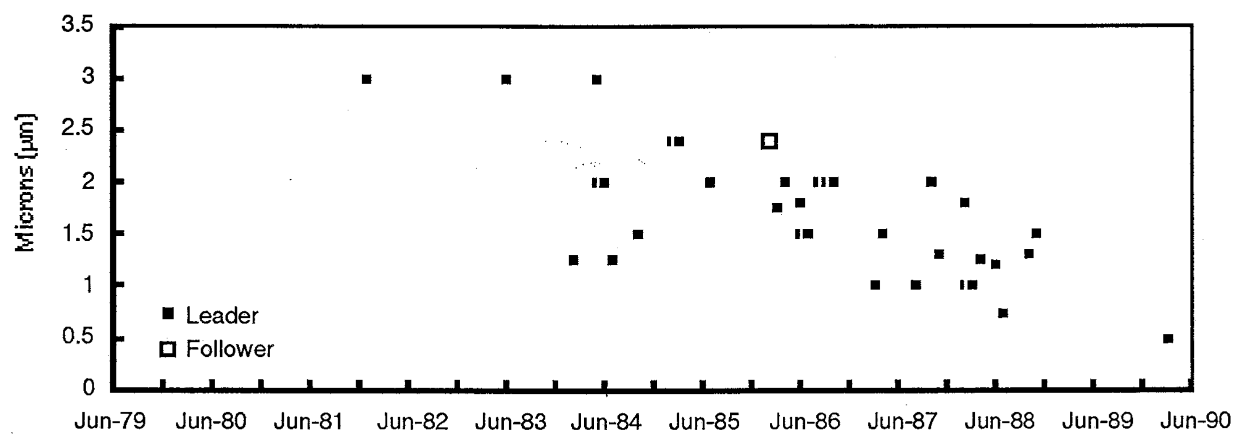

Fig. 50--DSP feature sizes, leaders vs. followers

Introductory Prices

As might be expected, DSPs produced by firms using the follower strategy are lower-priced than those introduced by leaders. The impression from the chart of introductory prices, shown in Figure 51, is confirmed when performance is taken into account in Figure 52.

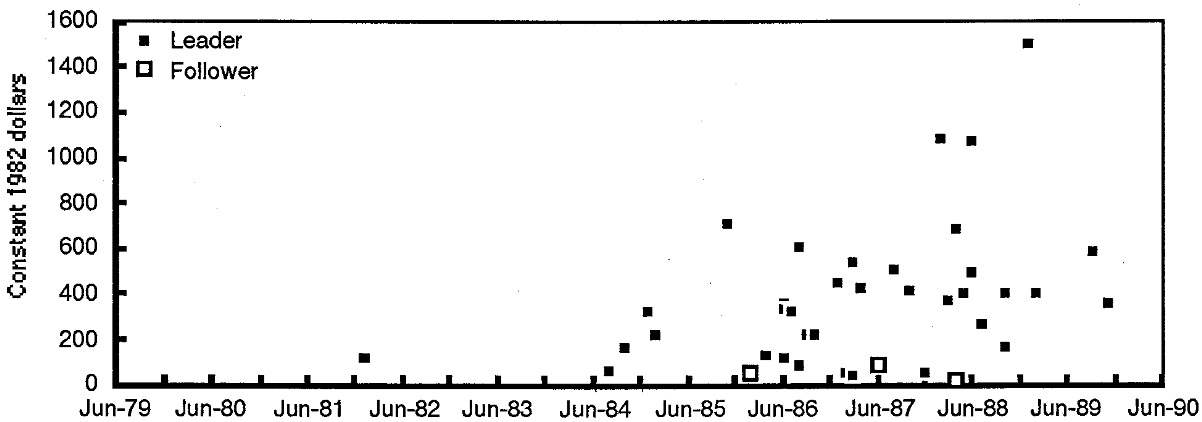

Fig. 51--DSP introductory prices, leaders vs. followers

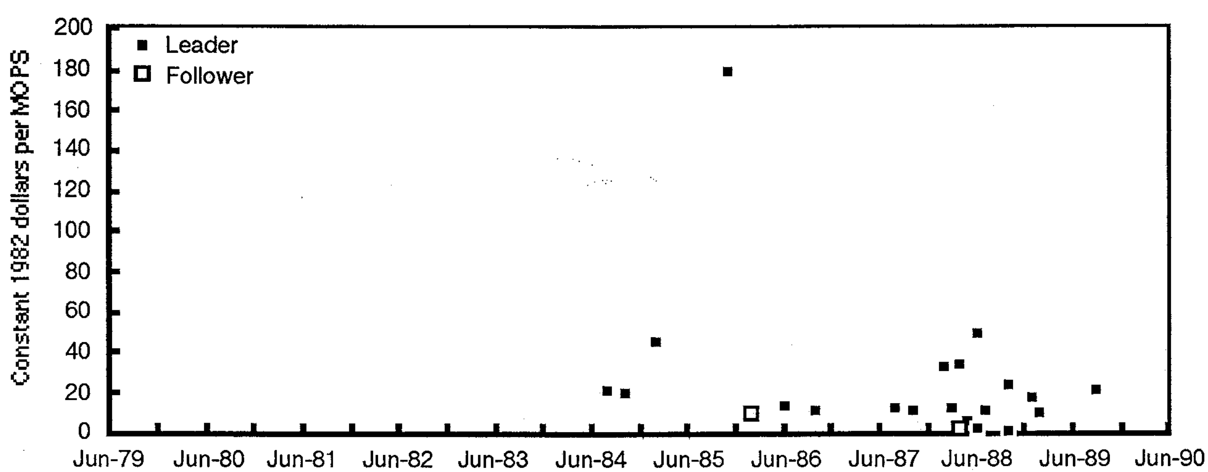

Fig. 52--DSP price/performance ratio, leaders vs. followers

Hypothesis 4 As It Applies to DSPs

Hypothesis 4 stated that the government could look to technology followers in order to purchase ICs which are not much further behind in technology, but cost considerably less. There is insufficient data to determine whether this hypothesis holds in DSP markets, although the limited price information indicates that DSPs produced by technology followers do, in fact, cost less.

FINDINGS

Digital signal processors are interesting to compare with general purpose microprocessors, discussed in Section IV. Unlike general purpose microprocessors, military DSPs examined in this study have been either ahead of or on par with commercial DSPs, even without taking into account building-block components which have been in heavy use for military applications. In fact, if the TRW/Motorola CPUAX gets quickly incorporated into military systems, military DSPs will be considerably ahead of commercial ICs. This is quite a weak statement, given the often-expressed belief that digital signal processing was invented for military applications and was not "discovered" for commercial applications until the mid-1980s.[3] However, most military systems use building-block components which were not part of this study, so the results cannot be generalized.

Another difference between general purpose microprocessors and DSPs is the role of systems-oriented firms. While these firms did not play a significant role in general purpose microprocessors, they have been leaders in digital signal processing. The DSPs produced by systems-oriented firms have led along all dimensions examined in this study, and this leadership was confirmed by regression analysis. Many of these firms participated in both commercial and military markets.

Finally, there is a possibility that military DSPs could skip a generation if the CPUAX can be quickly moved from the laboratory into systems. General purpose microprocessors have not had such an opportunity. Neither did earlier generations of DSPs, which showed a smooth progress along all characteristics examined in the study.

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[3]This has shown up in a number of articles, including among others C. Tyler, "Southcon/83 Sees Interest in Digital Signal Processing," *Electronic Design*, January 20, 1983, p. 40; D. Fair and B. Windsor, "CMOS DSP Components Target New Military Applications," *Defense Electronics*, April 1986, pp. 105-116; D.A. Mindell, "Dealing With a Digital World," *Byte*, August 1989, pp. 246-256.

VI. STATIC RANDOM ACCESS MEMORIES

In this section we turn our attention from processor markets to memory markets. Memory markets are quite different from those discussed in Sections IV and V. Processors are devices that heavily depend on their operating systems for running software, which makes different processors incompatible; memory ICs are basically commodity devices. As long as standard interfaces are available, a manufacturer of electronic equipment can use different memory devices within a line of equipment. Because of the commodity nature of memory chips in general, and static random-access memories (SRAMs) in particular, success in this market depends much more on price and raw speed than does success in processor markets, where ease of programming and compatibility with other equipment are important.

SRAMs, like dynamic RAMs (DRAMs), are good demonstration vehicles for design and manufacturing technology because of their simple structure. SRAMs are used in this way in commercial and military markets. Commercial developments in SRAMs are featured prominently at International Solid State Circuit Conferences (ISSCC) a few months to several years before the actual circuits come on the market. Many of the circuits that get introduced at ISSCC actually show up on the market. In military markets, SRAMs are used as deliverables in advanced R&D contracts.

Several trends have been in evidence in SRAM markets over the past ten years.

1. Access times have fallen. Very fast speeds are now available in small-storage-capacity SRAMs; speeds of larger-capacity SRAMs have also fallen drastically. SRAMs seem to have split into two categories: the larger SRAMs have been relatively slow, but low-power; small SRAMs are very fast, but consume more power and do not have much storage capacity, which makes them most suitable for fast caches. Microprocessors with which SRAMs work have been operating at greater clock rates, which has been one of the forces driving SRAM speeds down.[1] In an effort to gain even greater speed, some manufacturers have started to design their SRAMs to operate with specific processors without glue logic, creating a group of specialty, rather than commodity, SRAMs.

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[1]In order to operate at maximum speed, a processor must be able to access memory without "wait states," i.e., in a single tick of the clock. This means that memory access times must fall as clock speeds rise.

2. SRAM capacities have increased from between 4 and 16 kilobits, common ten years ago, to 1 megabit, available today. Although SRAM bit-count lags dynamic RAMs by factors of four to six,[2] the transistor counts of the two memory types have kept pace with each other.
3. SRAM manufacturing technologies have progressed over time from NMOS to CMOS to bi-CMOS. Greater density means faster circuit speed, but it also means greater power dissipation. The changes in manufacturing technology have permitted IC makers to make denser chips without increasing the speed-power product.
4. Per bit prices have fallen with every succeeding generation of memories.

CLASSIFYING FIRMS

The group of firms which produces SRAMs is different from the group which participates in processor markets. Table 6.1 lists firms whose products are included in the database for this study, together with the classification according to the taxonomy presented in Section II. Both commercial and military markets are represented. However, the majority of the firms whose ICs are used in the analysis are classified as component-oriented technology leaders. Systems-oriented suppliers do manufacture their own memories (IBM is the prime example), but the information about these is sparse in open literature, including literature about the computer systems produced by systems firms, since SRAMs are generally not the featured ICs of such systems.

Several Japanese firms are represented in the analysis, all of them classified as component-oriented firms because this is their orientation in U.S. markets. Japanese firms have played a significant role in advancing the state of the art in SRAMs. Papers by Japanese firms have been represented at ISSCC meetings over the past 10 years, and many significant improvements in SRAM design, manufacturing technology, and performance were reported by them.

Of the firms which appear in Table 6.1, Texas Instruments (TI) and National Semiconductor built SRAMs for Phase 1 of the DoD's VHSIC Program. (TRW also built an SRAM, but it is not a regular SRAM producer.) Both firms were dropped after Phase 1, but should have been able to benefit from technology developed in the Program. In fact, in 1987 Texas Instruments left the commercial SRAM market, although it continued to provide SRAMs to the military.

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[2]A DRAM memory cell is composed of a single transistor and a capacitor. An SRAM cell is composed of either four or six transistors.

Table 6.1

CLASSIFICATION OF SRAM PRODUCERS

Firm Name	Commercial or Military	Systems or Components	Leader or Follower
AMD	C	Co	L
Cypress	C, M	Co	L
EDI	M	Co	L
Fairchild	C	Co	L
Fujitsu	C	Co	F, L
GTE	M	S	L
Harris	M	Co	L
Hitachi	C	Co	F, L
IBM	C	S	L
ICI	M	Co	L
IDT	C, M	Co	F, L
ILC	C	Co	L
Inmos	C	Co	L
Intel	C, M	Co	L
Intersil	C	Co	L
Lattice	C	Co	L
Micron	C, M	Co	L
Mitsubishi	C	Co	L
MOS	C	Co	L
Mosaic	C	Co	L
Mostek	C, M	Co	F, L
Motorola	C	Co	L
National Semi	C	Co	L
NEC	C	Co	L
Nippon	C	Co	L
Paradigm	C	Co	L
Performance	C	Co	L
RCA (GE)	C, M	S	L
Saratoga	C	Co	L
Synertek	M	Co	F
TI	C, M	Co	F, L
Toshiba	C	Co	L
VLSI	C	Co	L

PRODUCT EVALUATION

SRAMs have undergone a significant evolution during the 1980s. 64-kbit SRAMs were the highest capacity SRAMs introduced at the 1981 ISSCC by Nippon Electric and NEC, and were manufactured in 1.5-µm NMOS. Texas Instruments and IBM introduced small, fast 16-kbit RAMs. TI also created a demonstration 4-kbit MOS SRAM for military markets with 1.25-µm features and a 22-ns access time, more than twice as fast as the 50-ns military SRAM it was producing at the time. Intel introduced the first

production 64-kbit chip into the commercial market during 1981, and a variety of firms produced 16-kbit ICs, the most advanced commonly available SRAMs. Manufacturing technology used for producing these advanced ICs contrasts with 3-μm line widths which were commonly in production in 1981.

64-kbit SRAMs began to appear in the market as samples in 1982 and were available from a variety of firms in 1983. They were still the highest bit-count SRAMs at the 1983 ISSCC, but the technology with which they were manufactured had improved. IBM Laboratory in Böblingen, Germany, introduced a 64-kbit bipolar SRAM with 25-ns access times, while CMOS SRAMs of the same densities had access times of about 70 ns.

The 1984 ISSCC saw the introduction of the first 256-kbit SRAM, manufactured with 1.2-μm NMOS gates and 1.5-μm PMOS gates. That was the year that Texas Instruments' first VHSIC chip, a 72-kbit SRAM, was made functional. By 1985, several firms were introducing 256-kbit SRAMs at ISSCC, and the first commercial 256-kbit SRAM was introduced into the market by NEC.

SRAMs of 1 Mbits were introduced at the 1987 ISSCC with access times of 25 ns to 42 ns. All four of these 1-Mbit SRAMs were introduced by Japanese firms. At the same time, access times of bipolar SRAMs improved considerably, with 5-ns 64-kbit SRAMs from Fujitsu and a 7-ns 64-kbit SRAM from Hitachi. Although the Japanese were most aggressive in the SRAM market, Motorola and IBM were very active as well, developing fast versions of 256-kbit chips.

1989 ISSCC saw the introduction of the first 4-Megabit SRAM from Sony, Japan. Access times for 1-Mbit SRAMs dropped to as low as 10 ns.

In the military market, developments in rad-hard manufacturing have led to a development of rad-hard 64-kbit CMOS SRAMs by IBM and Honeywell, using VHSIC manufacturing technology and Strategic Defense Initiative (SDI) funding, and a start of work on 256-kbit SRAMs. Several firms, including Harris, AT&T and Texas Instruments have participated in a variety of rad-hard technology programs, and different technologies were used including CMOS-bulk silicon, CMOS-SOI and CMOS-SOS. However, as SDI encountered opposition and reduced funding, so did rad-hard research, delaying and scrubbing some of the projects. Plans to develop a 1-megabit rad-hard SRAM by 1991 were scrubbed, for instance, putting rad-hard SRAM capacities further behind their non-rad-hard military counterparts.[3]

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[3]L. Burgess, "SDIO's Budget Cuts Hit Rad-Hard IC Research," *Military Aerospace Electronics*, April 1990, pp. 7-8.

With this summary of SRAM evolution, let us now proceed to the evaluation of SRAMs along six characteristics: memory capacity (number of memory bits), access speed, feature size, power dissipation, speed-power product, and price (both introductory price and price per bit).

Commercial vs. Military

The charts below show comparisons of commercial and military SRAMs. The ICs shown in these charts include SRAMs developed for radiation hardness through several R&D programs undertaken by government agencies and military contractors.

Memory Capacity

Figure 53 shows the changes in the capacity of SRAMs over time. Since the changes are exponential in nature, a number of low-bit-count ICs appear as falling on the horizontal axis--in fact, none of the chips shown have less than 4-kilobit capacity.[4] As discussed above, during the ten year period under analysis the storage capacity of SRAMs progressed from 4-kbit to 1-megabit ICs, which contain more than 4 million transistors. Because capacity increases as powers of 2, the change from one level to the next is not continuous, and is usually characterized by a factor of 4. In order to improve the resolution of the chart, Figure 54 shows only low-capacity SRAMs. As both figures indicate, despite the presence of higher-capacity SRAMs in the market, lower capacity ICs continue in production, and sometimes contain novel features, such as battery back-up.

Commercial ICs have led the market in memory capacity. While SRAMs of many different sizes are being manufactured at any given time, the highest-capacity SRAMs were developed for commercial markets. Military SRAMs have been several months behind, the time which corresponds to the time described by industry as needed for testing and packaging redesign to accommodate greater temperature range required for military ICs.

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[4]Bit counts for memories are powers of 2. Therefore, a "4-kilobit" SRAM actually stores 2^{12} or 4,096 bits, a "64-kilobit" unit stores 2^{16} or 65,536 bits, a "256-kilobit" unit stores 2^{18} or 262,144 bits (although it derives its designation from 64 x 4 = 256), and a "1-megabit SRAM" can store 2^{20} or 1,048,576 bits. The chart reflects the actual bit count rather than the conventional designation.

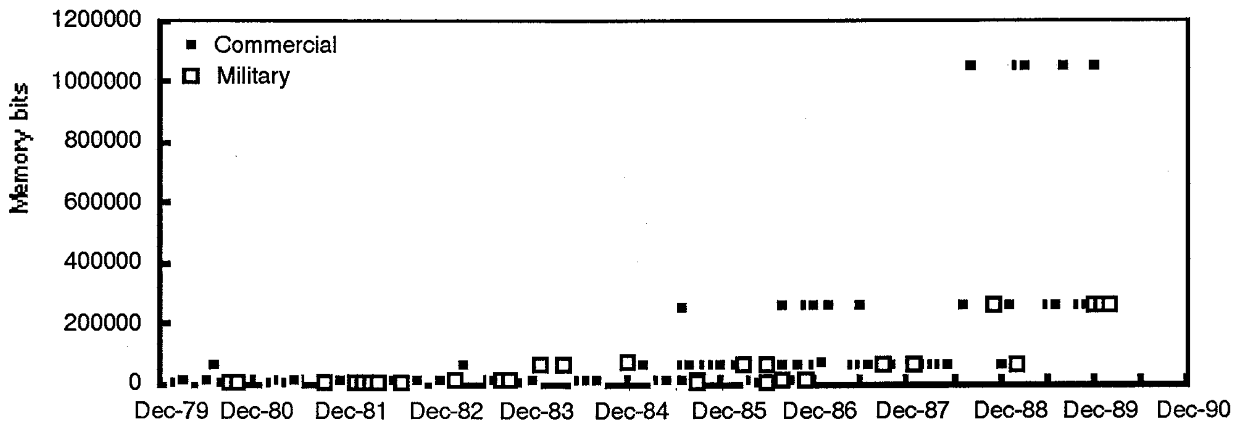

Fig. 53--SRAM bit levels, commercial vs. military

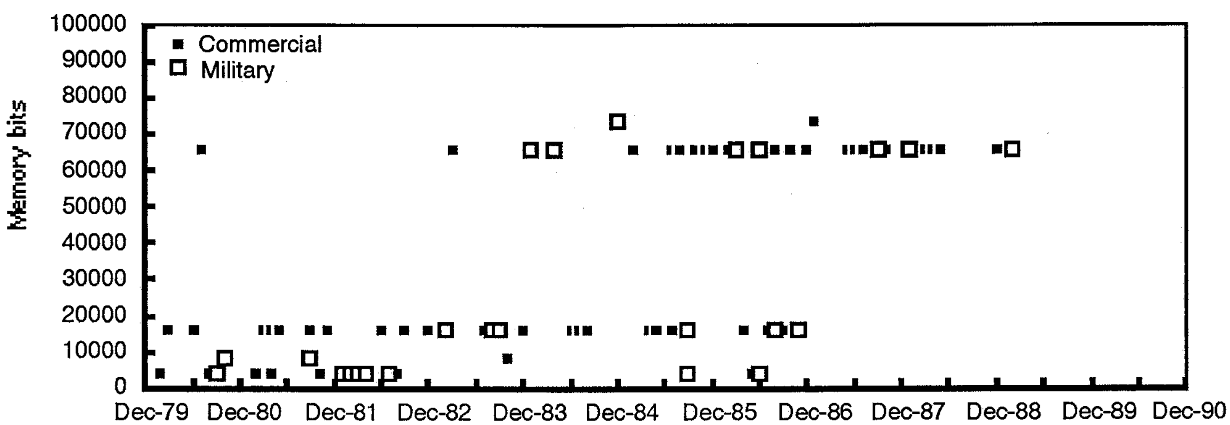

Fig. 54--Lower capacity SRAMs, commercial vs. military

Access Time

Figure 55 shows the changes in access time over the past 10 years. Although commercial SRAMs have led the advance along this dimension, the military has not been far behind. There does not appear to be a period when either commercial or military access times take a significant leap forward, including the post-VHSIC period of 1986-

1987, when VHSIC-qualified SRAMs were being introduced. Commercial markets have kept pace with military markets along this dimension even during the time when military ICs were significantly and specifically improved through the VHSIC Program. Commercial access times usually appear below military ones, although not always to the left (i.e., earlier in time).

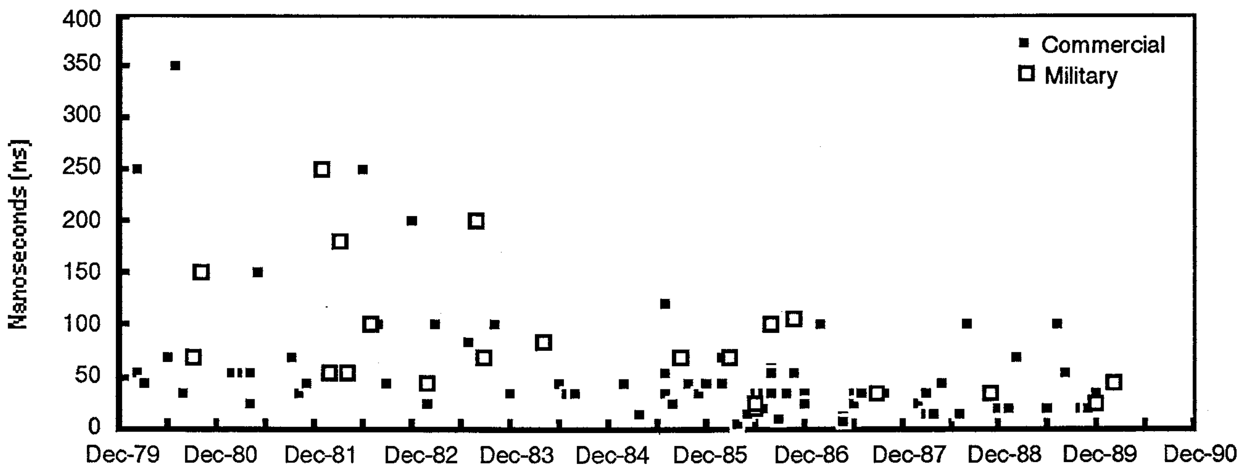

Fig. 55--Access time, commercial vs. military

Feature Size

Figure 56 shows feature sizes of commercial and military SRAMs. Data are not abundant, especially for military SRAMs, but the military leads during 1985 and 1986, the period when VHSIC Phase 1 technology was entering the market. Commercial technology caught up quickly, however. In fact, commercial industry was producing experimental chips with 1.2- to 1.5-μm technology starting in 1984.

VHSIC Phase 2 technology, with its 0.5-μm line widths, has not yet appeared in mass-produced SRAMs either for military or commercial applications.

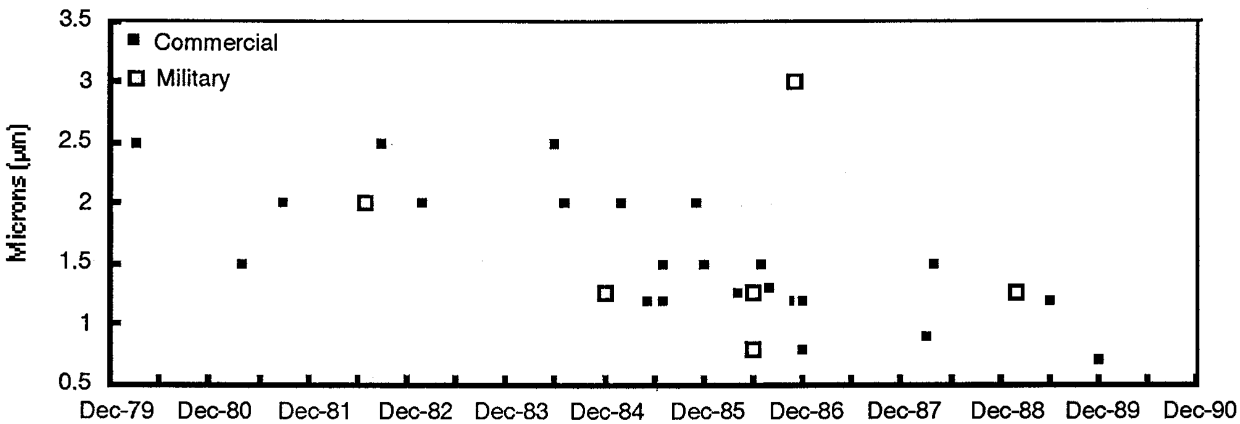

Fig. 56--Feature size, commercial vs. military

Power Dissipation

Figure 57 shows SRAM power dissipation, a parameter which has remained within remarkably narrow boundaries, given the significant increase in memory capacity which has taken place during the same time period. A single commercial outlier, coming in at 4,500 mW, was omitted from the figure--all other points in the data base are shown. Military and commercial data points are well intermixed; points corresponding to military SRAMs appear in the middle of the range without showing significant differences from their commercial counterparts.

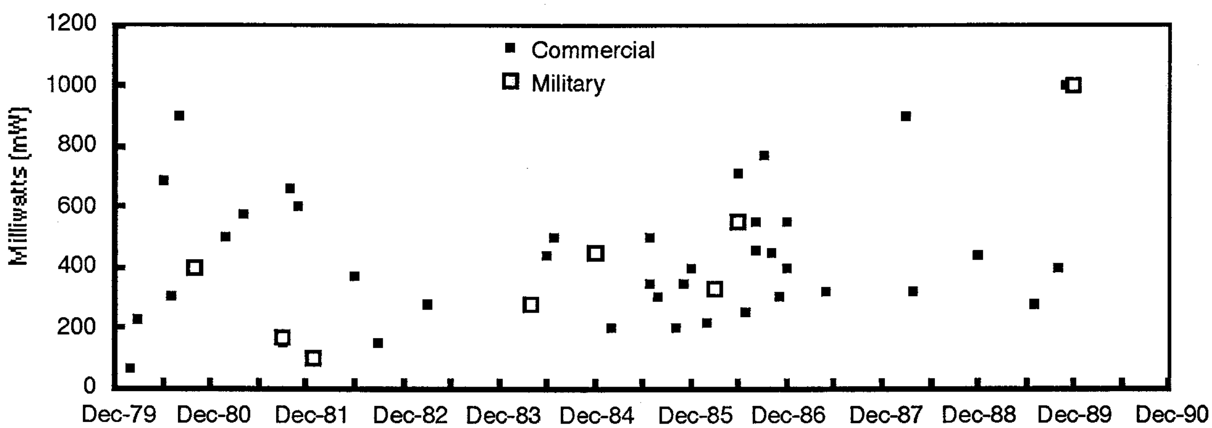

Fig. 57--SRAM power dissipation, commercial vs. military

Speed-Power Product

An interesting parameter is the speed-power product, shown in Figure 58. The parameter is derived by multiplying access time by power dissipation. This parameter measures the trade-off made by the manufacturer between circuit speed and power dissipation. It has been possible for a long time to make fast SRAMs, but at the cost of generating large amounts of heat, which is difficult to remove from the system. With the change of manufacturing technology from NMOS to CMOS, power dissipation dropped *and* circuit speed improved (mainly due to the decrease in the distance between transistors with decreased feature sizes). As a result, the product of the two has remained relatively constant over time. Since military SRAMs have shown somewhat higher access times but no significant difference in IC power dissipation, they also show speed-power products in the upper part of the range, but the differences between commercial and military SRAMs are small.

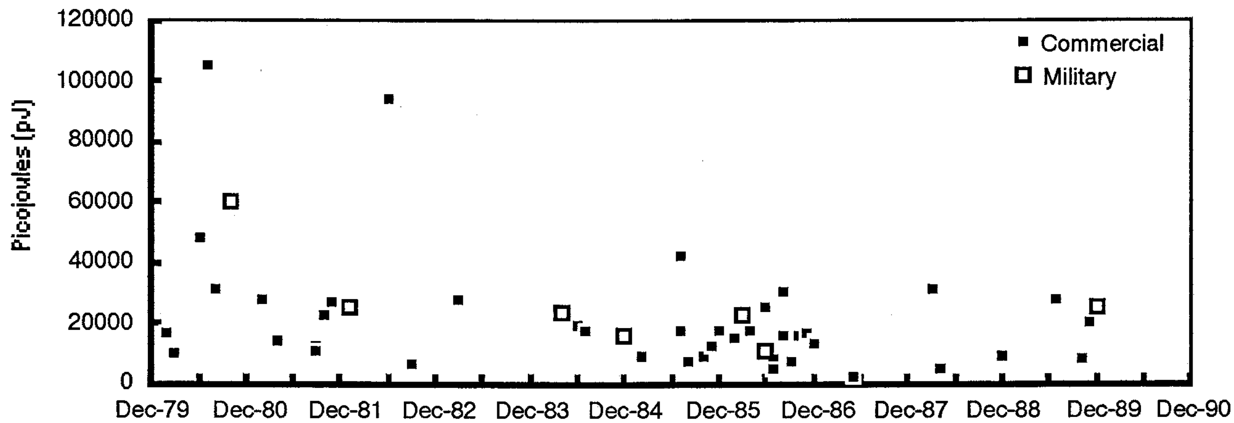

Fig. 58--SRAM speed-power product, commercial vs. military

Introductory Price

Figure 59 shows introductory prices for commercial and military SRAMs in constant 1982 dollars. (Introductory prices are used, with the understanding that these prices drop in time due to the effects of learning and experience curves in the industry.) Here, the differences between commercial and military SRAMs are clearest of all the parameters examined so far. With a single commercial exception, all high-priced SRAMs are military, and the price differential is on the order of factors of two or three. Three of the highest-priced military SRAMs are rad-hard, produced by Harris and RCA. Their high price may be explained by their specialized nature.

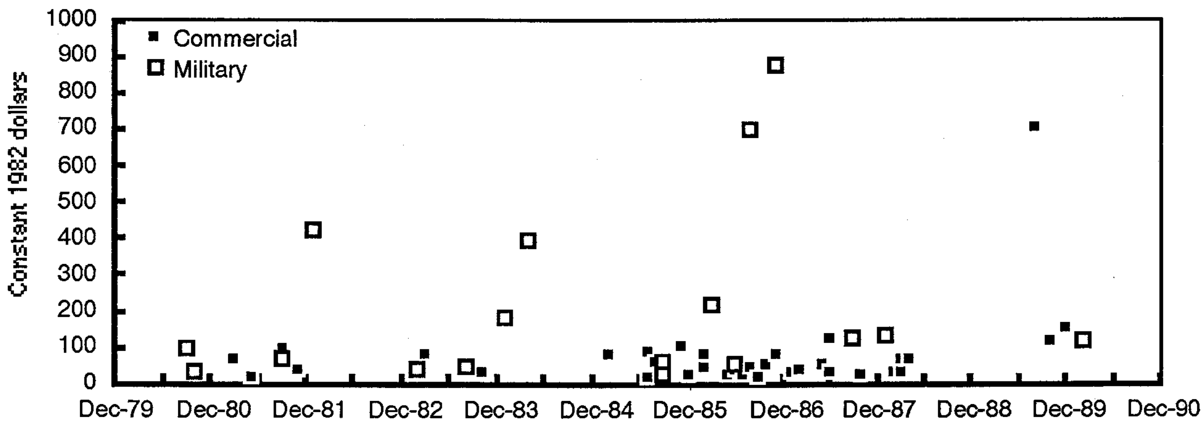

Fig. 59--SRAM introductory prices, commercial vs. military

Figures 60 and 61 show prices per bit of memory for commercial and military SRAMs. This is done to account for the fact that lower-capacity ICs may also be lower priced and, therefore, may distort the price comparison. Comparing commercial and military prices per bit leads to the same conclusion as the comparison of introductory prices: military SRAMs are considerably more expensive than their commercial counterparts. In fact, even when the five military "outliers" are excluded from the chart (Figure 61) the picture does not change: the difference between per-bit prices for commercial and military SRAMs narrows, but does not entirely disappear.

Integration of Multiple Characteristics

Above we examined individual SRAM characteristics. With the exception of a brief period when military feature sizes led commercial, commercial SRAMs were ahead of military SRAMs in all other parameters. In order to determine whether manufacturers of commercial and military SRAMs make different trade-offs between IC

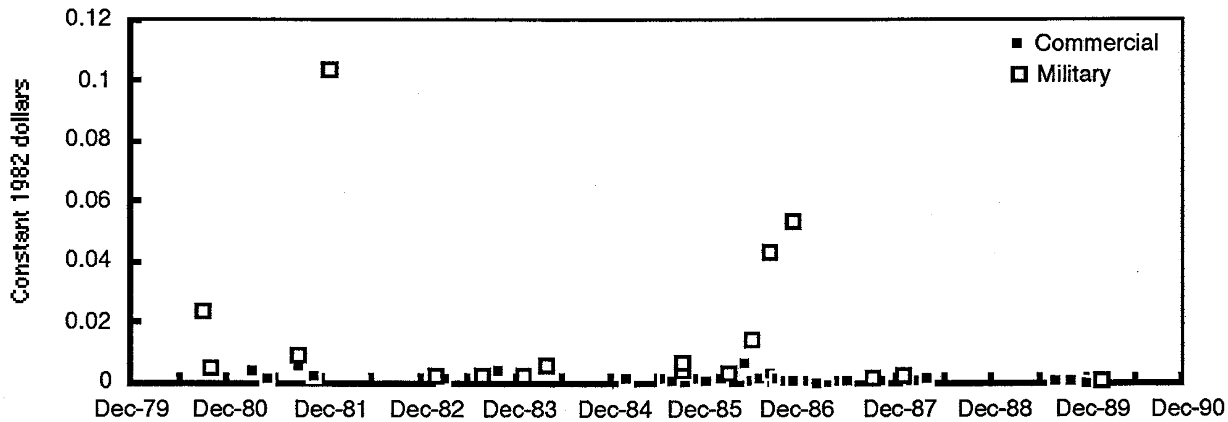

Fig. 60--SRAM price per bit, commercial vs. military

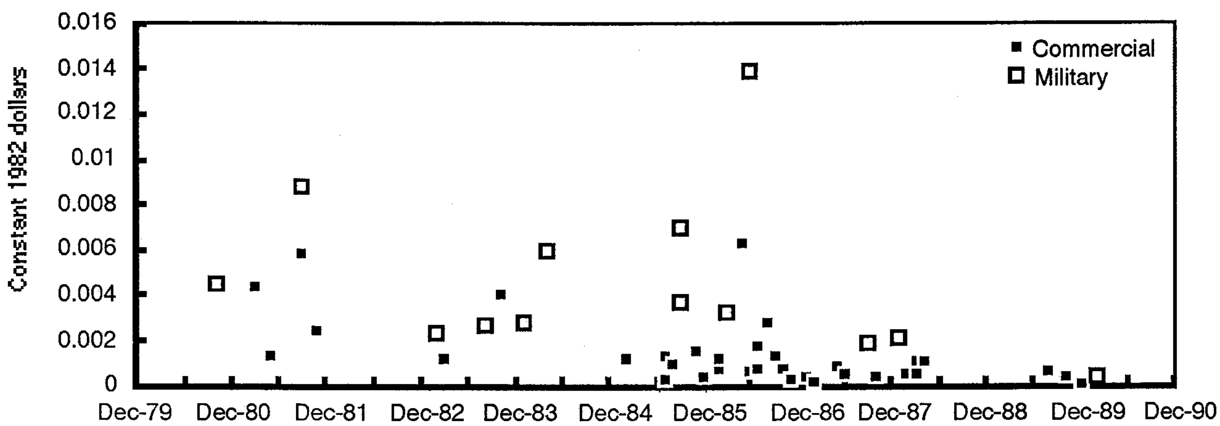

Fig. 61--SRAM price per bit (highest-price ICs excluded), commercial vs. military

characteristics, a multiple regression analysis was performed, relating all SRAM characteristics to the month of introduction (the dependent variable), and including a dummy variable to distinguish commercial and military SRAMs. The results of the regression analysis are shown in Table 6.2.

Table 6.2

REGRESSION RESULTS--COMMERCIAL VS. MILITARY SRAMS

Variables	Regression 1	Regression 2	Regression 3	Regression 4	Regression 5	Regression 6
Constant	-138.159 (0.000)	- 91.456 (0.000)	- 96.495 (0.000)	- 98.689 (0.000)	- 89.624 (0.000)	-145.945 (0.000)
Access time	- 0.128 (0.028)	- 0.198 (0.000)	- 0.196 (0.000)	- 0.199 (0.000)	- 0.195 (0.000)	- 0.133 (0.019)
Ln No. memory bits	20.424 (0.000)	16.950 (0.000)	17.254 (0.000)	17.404 (0.000)	16.818 (0.000)	20.853 (0.000)
Power dissipation	0.009 (0.044)					0.009 (0.052)
Price per bit-FI ($82)	-860.647 (0.442)		450.785 (0.005)	393.100 (0.019)	-136.608 (0.686)	
Military dummy	- 1.271 (0.875)			5.322 (0.290)		
Rad-hard dummy	126.004 (0.254)	35.214 (0.001)			43.185 (0.054)	40.988 (0.051)
Adjusted R^2	0.715	0.717	0.706	0.706	0.715	0.724

NOTE 1: Numbers in parentheses represent the significance level of the coefficient, i.e., 0.010 means that the coefficient is significant at the 1% level.

NOTE 2: "FI" in the variable name means that the data used in the regression was augmented by the technique discussed in Section II.

Six regressions are shown in the table. Regression 1 includes a variety of variables and two dummies, one to distinguish commercial SRAMs from military, and one to distinguish radiation-hard SRAMs from ones not designed specifically for radiation resistance. The sign on the constant is negative, reflecting the placement of the zero point on the time scale. The signs on other variables are as expected: sign of "Access time" is negative (faster SRAMs are developed later than slower ones), sign of "Ln No. of Memory Bits" is positive (larger-capacity SRAMs are developed later), sign of "Price per bit" is negative, reflecting the falling cost of price per bit of memory (as shown in charts above), sign of the "Rad-hard dummy" is positive (rad-hard SRAMs are developed later than non-rad-hard ones). Two signs are interesting to note: the sign of "Power dissipation" is positive, which is interesting because the chart shows this trend only slightly. The other interesting sign to observe is the negative sign on the "Military dummy." The variable is not significant, however, and the small value of the coefficient in this case reflects the fact that there is no significant difference between the introduction times of commercial and military SRAMs, as long as the military ICs are not designed for radiation hardness.

Regressions 2 through 5 reflect various other combinations of variables. It is interesting to note that when the variable "Price per bit" is present without the rad-hard dummy, its sign becomes positive. Rad-hard SRAMs are so much more expensive than their non-rad-hard counterparts that they exert a significant influence on the sign of the "Price per bit" variable and create a regression which differs in meaning from the picture of the data seen above. It is interesting to note that "Price per bit" is not significant in any of the regressions in which it has a negative sign. This is probably a reflection of the fact that when a new generation of SRAMs is introduced, price is not a significant consideration. It becomes significant later, of course, but the database of this study does not reflect the fact because it contains only prices at the time of introduction.

The best fit, with all variables significant at the 5% level, is regression 6. This regression has a high Adjusted R^2, explaining much of the variation in the data with relatively few variables, and all the coefficients are significant and have expected signs. It is interesting to note that neither "Price per bit" nor the military dummy appear in the equation, although the rad-hard dummy does.

Hypothesis 1 As It Applies to SRAMs

Hypothesis 1 stated that commercial markets can be expected to be on par with or lead military markets in technology. The figures indicate that data support this

hypothesis. Military SRAMs lead only in feature sizes and during a short period of time. In all other times and characteristics, commercial SRAMs lead. The differences between the two markets are small, however. Figures show that data points reflecting military and commercial SRAMs are generally intermixed throughout the range of interest, although military data points tend to appear in the upper part of the range.

The exception is rad-hard SRAMs. Rad-hard SRAMs are significantly different from both commercial and non-rad-hard military SRAMs. They are much more expensive than other military SRAMs, and are developed considerably later in comparable capacities.

Generation Skipping

As discussed above, there is no indication that firms in either commercial or military markets skip generations, this despite the fact that the VHSIC Program was specifically designed by the government to provide military contractors with advanced ICs, including SRAMs. There is little difference between commercial and military SRAMs, except in the case of rad-hard SRAMs, so there is reason to believe that the strategy of skipping generations has not produced more advanced military SRAMs than would otherwise be available. SRAM data support Hypothesis 2.

Systems vs. Components

As noted at the opening of this section, the information on SRAMs produced by systems-oriented firms is sparse. The information presented below is, therefore, more in the nature of description and conjecture than analysis. Although information about the chips IBM produces for use in their systems is scarce, the firm has been active in SRAM research and innovation, as indicated by papers presented at the ISSCC. As mentioned above, IBM Laboratory in Böblingen, Germany, introduced a very fast 64-kbit bipolar SRAM with access times about one-third of CMOS SRAMs of the time. In 1988, IBM was one of five companies which introduced a 1-Mbit SRAM at ISSCC. IBM was using a 0.7-μm manufacturing process, and presenting the most flexible design, configurable by laser personalization. Except for IBM, which is a significant participant in both commercial and military markets, other U.S. systems-oriented firms were not as well represented in ISSCC. However, the scarcity of data should not be confused with lack of advanced SRAMs created by systems-oriented firms.

Memory Capacity

Figures 62 and 63 present information on the capacities of SRAMs fabricated by systems- and component-oriented firms. As in the case of the commercial-military comparison, a closer look at lower-capacity SRAMs is presented in a separate figure.

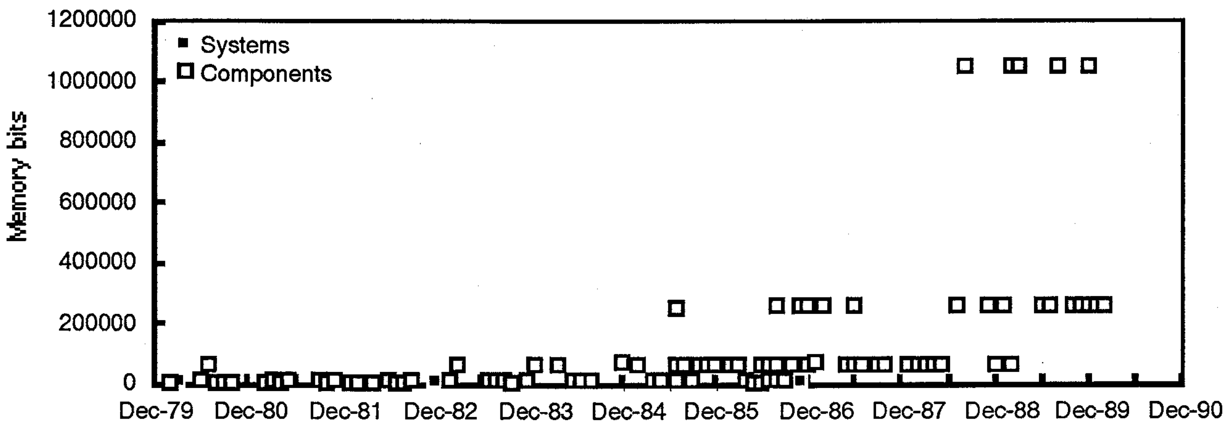

Fig. 62--SRAM bit levels, systems- vs. component-oriented firms

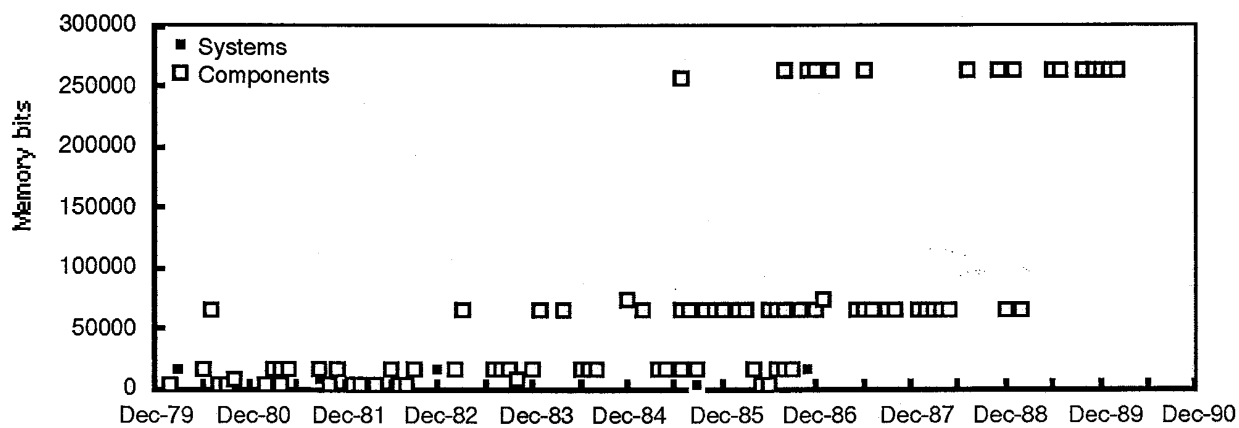

Fig. 63--Lower capacity SRAMs, systems- vs. component-oriented firms

The higher-capacity SRAMs in both figures are produced by component-oriented firms, although there is a number of lower-capacity SRAMs shown in Figure 63, produced by

systems firms. With the exception of IBM's 16-kilobit SRAM introduced in February 1980, component-oriented firms lead the field along this dimension.

Speed

Figure 64 shows access times for SRAMs built by systems- and component-oriented firms. The few data points of systems-oriented firms that are available show ICs that are generally slower than those produced by the component-oriented firms. The early IBM IC is, once again, a stand-out by having an access time less than 50 ns in 1980.

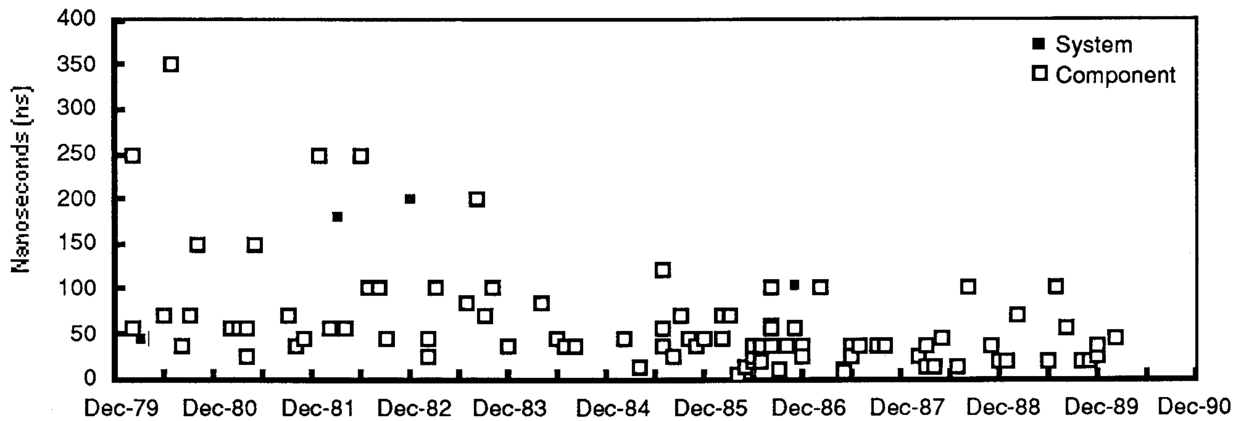

Fig. 64--Access times, systems- vs. component-oriented firms

Feature Size

There is almost no information on feature sizes used by systems-oriented firms, as shown in Figure 65. The only two points in the database place these SRAMs behind the ICs produced by component-oriented firms, but there is not even sufficient data upon which to base speculations about this IC characteristic.

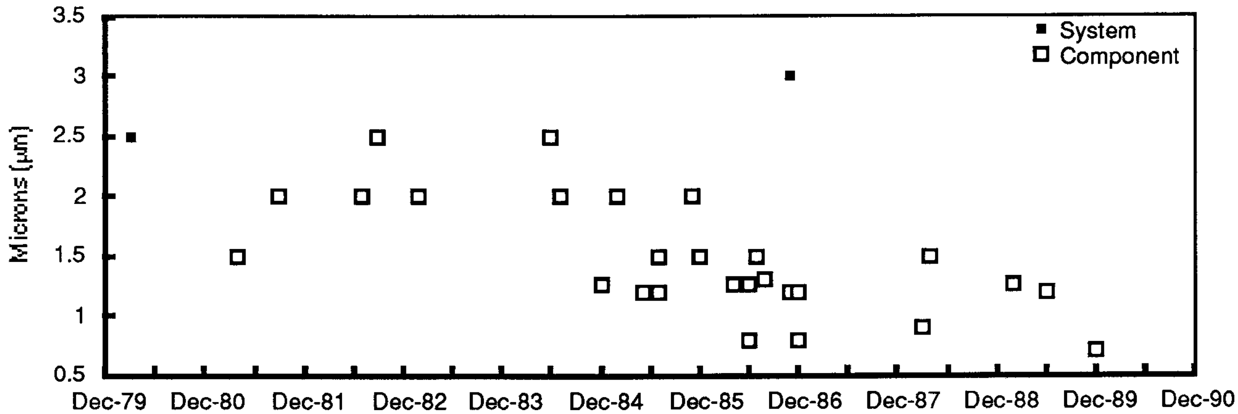

Fig. 65--SRAM feature sizes, systems- vs. component-oriented firms

Power Dissipation and Speed-Power Product

Figures 66 and 67 show the available information about circuit power dissipation and the speed-power product. There is almost no information available about systems-oriented firms, and no attempt is made to draw conclusions from the figures.

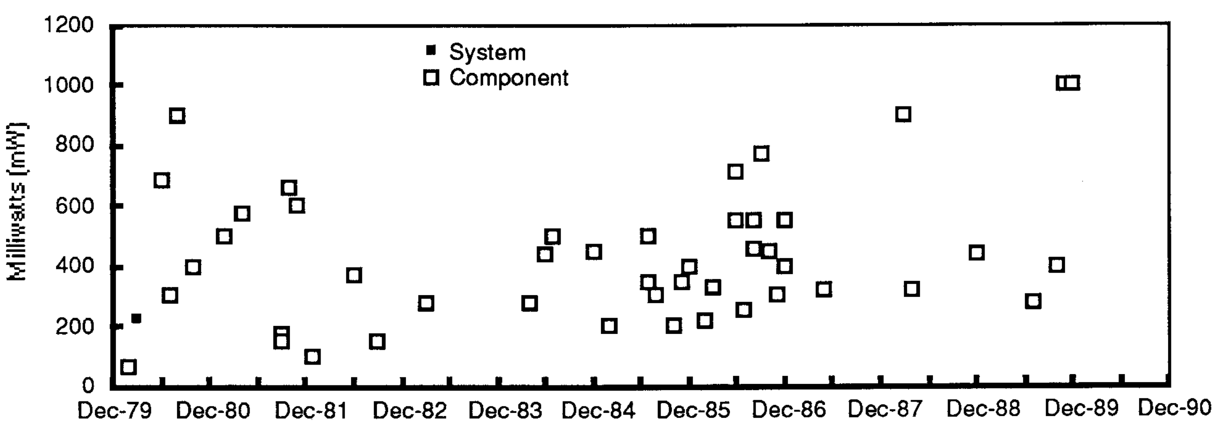

Fig. 66--SRAM power dissipation, systems- vs. component-oriented firms

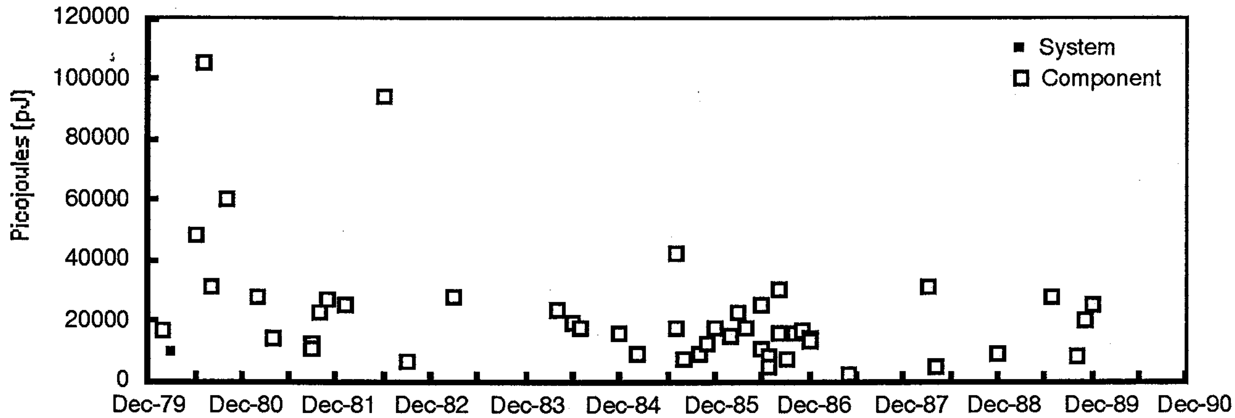

Fig. 67--SRAM speed-power product, systems- vs. component-oriented firms

Introductory Price

Figure 68 shows available information on SRAM introductory prices for systems- and component-oriented firms. The available information on systems-oriented firms is limited, but only one of the high-priced SRAMs is a product of a systems-oriented firm.

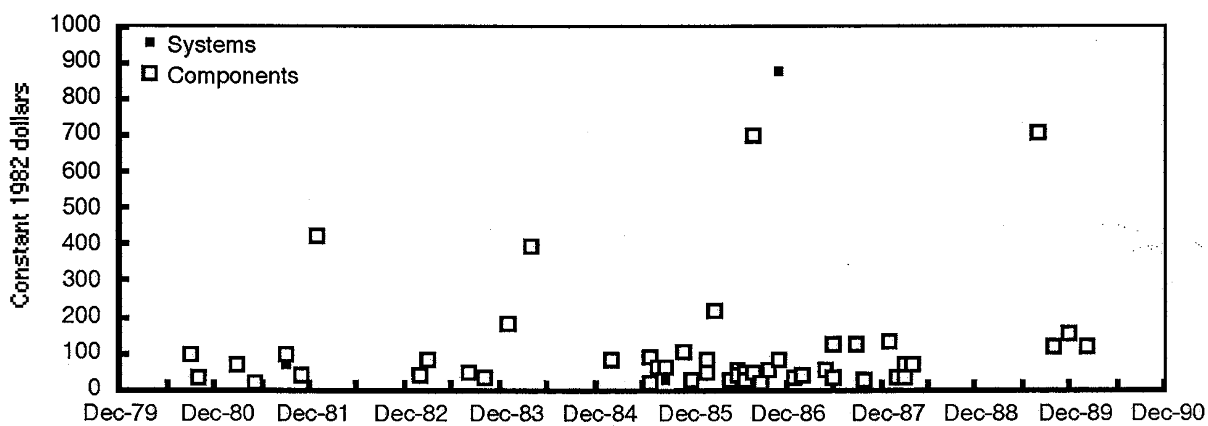

Fig. 68--SRAM introductory prices, systems- vs. component-oriented firms

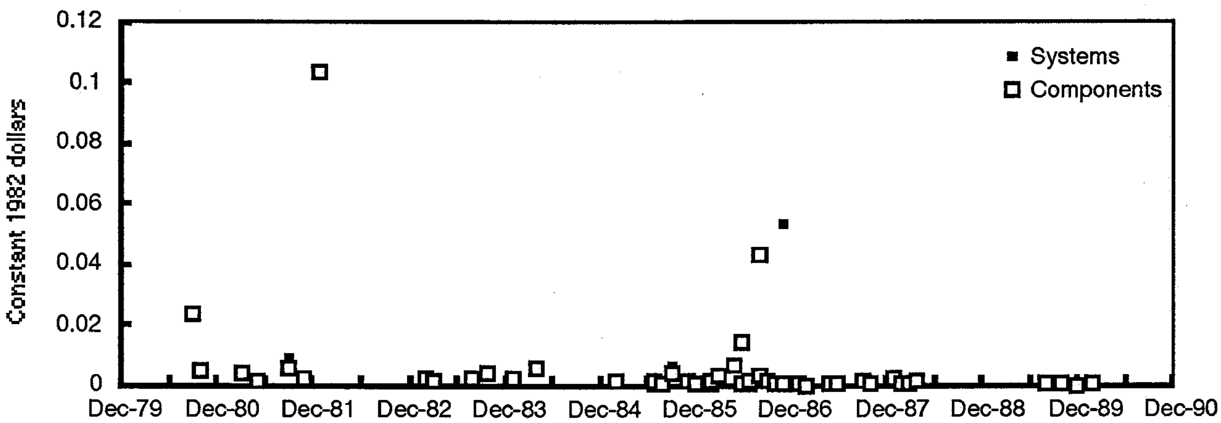

Fig. 69--SRAM price per bit, systems- vs. component-oriented firms

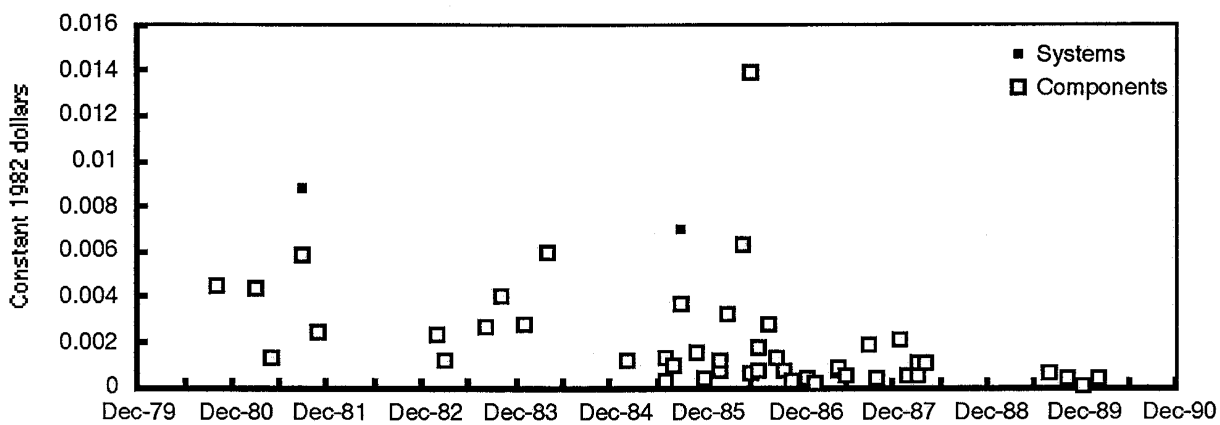

Fig. 70--SRAM price per bit (highest-price ICs excluded), systems- vs. component-oriented firms

Figures 69 and 70 show prices per bit for systems- and component-oriented firms. As in the case of commercial and military SRAMs, the second figure shows a closer look at the low-priced ICs. The few data points for systems firms available in both figures indicate that the prices of those firms' SRAMs are higher than those of their component-oriented counterparts. Part of the explanation for this may be that of the 6 points in the

data corresponding to systems-oriented firms, 4 are military SRAMs, which were shown above to be more expensive than their commercial counterparts.

Hypothesis 3 As It Applies to SRAMs

No attempt was made at integrative analysis in this case because there was not sufficient information on systems-oriented firms to make such analysis meaningful. The only statement which can (barely) be made from the available data is than systems-oriented firms tend to produce SRAMs which are more expensive, but the fact that most of them are military SRAMs can account for the differences in price.

Hypothesis 3 stated that funding military microelectronics R&D through systems-oriented firms delays the creation of most advanced components because systems firms do not have improvement of components as a priority. The data are not available in this case to evaluate the hypothesis.

Leader vs. Follower

Little information is available on firms using the technology follower strategy in SRAMs. Therefore, as in the case of systems- vs. component-oriented firms, only an overview of the data is presented.

Memory Capacity

Figures 71 and 72 present a view of changing memory capacity over time. Figure 72 presents a more detailed view of lower-capacity SRAMs, an area in which firms using the follower strategy are found. Although the data on followers is sparse, it is not surprising that they appear to be behind the leaders in the capacity of SRAMs they produce. However, the degree of difference in the two sets of ICs is surprisingly large.

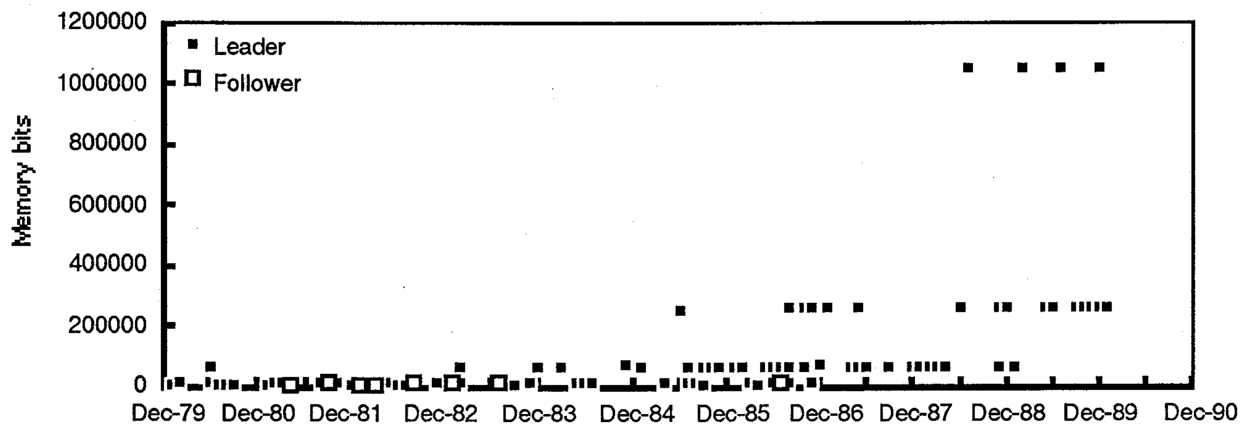

Fig. 71--SRAM bit levels, leaders vs. followers

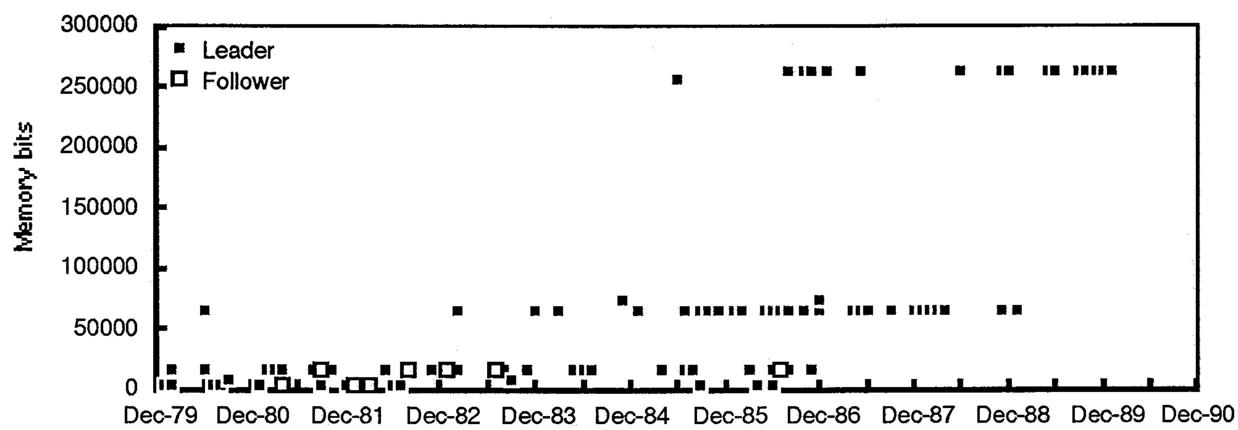

Fig. 72--Lower capacity SRAM bit levels, leaders vs. followers

Speed

Access times are shown in Figure 73. Although there are few points for firms using the follower strategy (and none after 1986), the available data points are toward the low end of access speeds. It must be noted, however, that Figure 72 indicated that

follower SRAMs have smaller capacity, and can, therefore, be made faster as technology progresses and chip size shrinks.

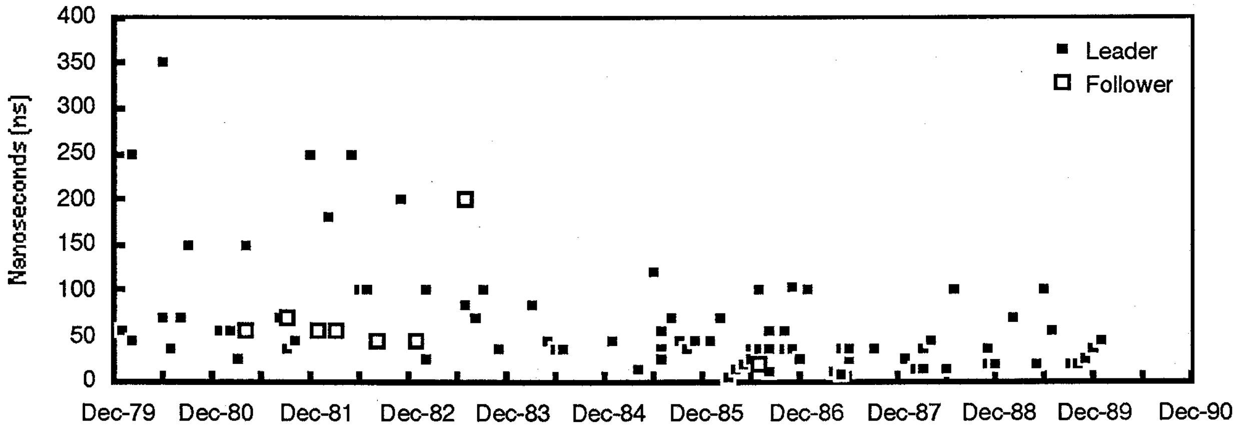

Fig. 73--SRAM access times, leaders vs. followers

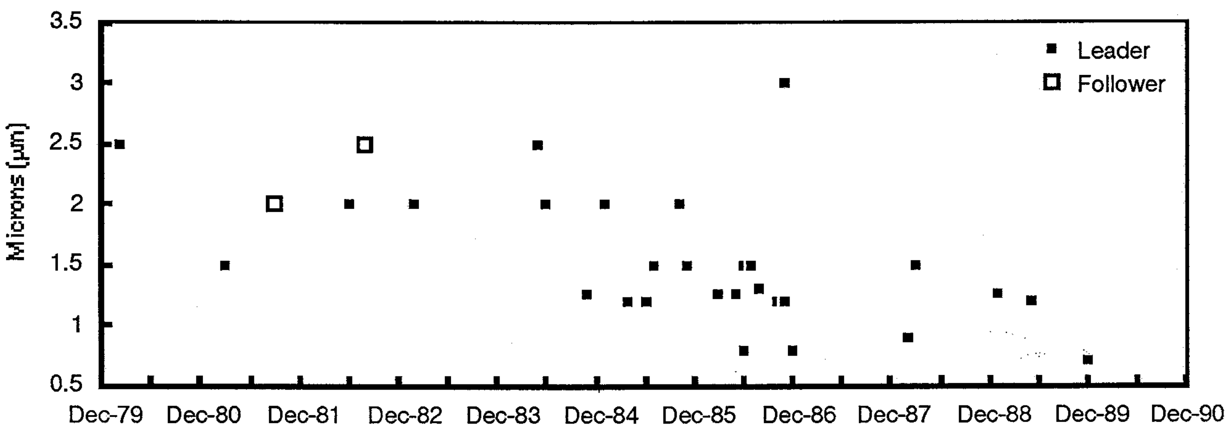

Fig. 74--Feature sizes, leaders vs. followers

Feature Size

Figure 74 shows the changes in feature size over time for leaders and followers. There is almost no information on firms using the follower strategy, so no conclusions can be drawn even on a tentative basis.

Power Dissipation and Speed-Power Product

Figure 75 shows power dissipation for leaders and followers. There are very few data points for follower SRAMs, but those given show low power dissipation, which is not surprising in view of the fact that these are ICs with small memory capacity. Small capacity is also the likely reason for the appearance of follower SRAMs on the low side of the speed-power products, shown in Figure 76.

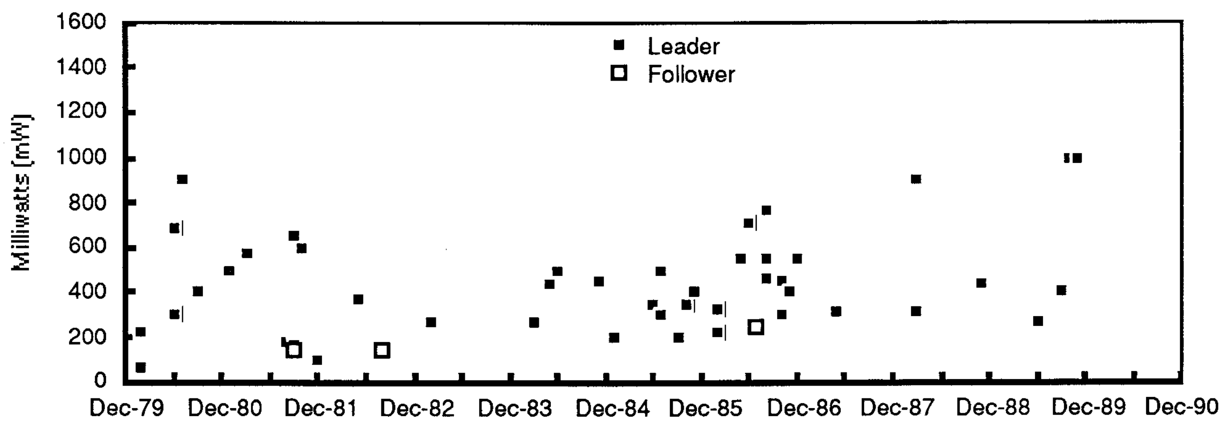

Fig. 75--SRAM power dissipation, leaders vs. followers

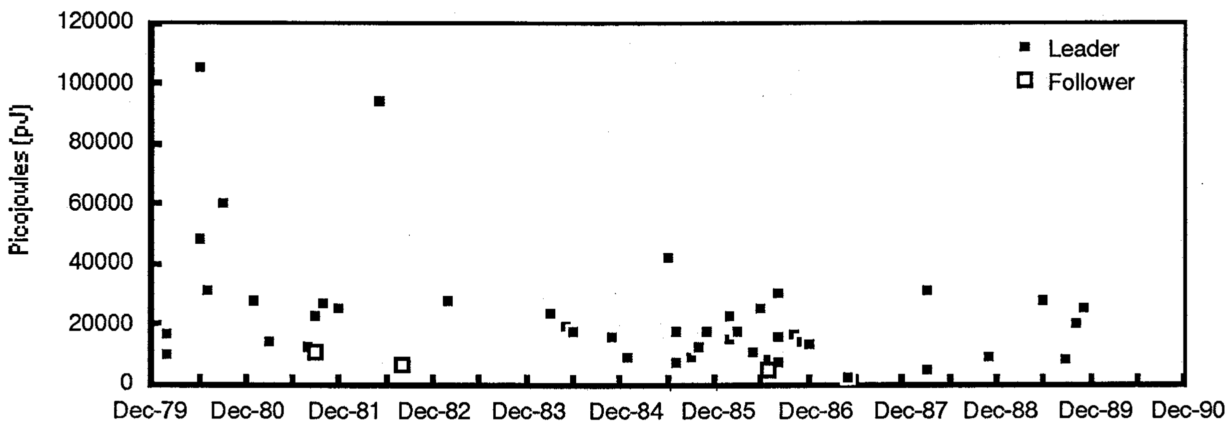

Fig. 76--Speed-power product, leaders vs. followers

Introductory Price

Figure 77 shows prices for SRAMs introduced by leaders and followers. As expected, prices for follower ICs are low--these are low-capacity ICs, introduced into the market where higher-capacity chips are already available.

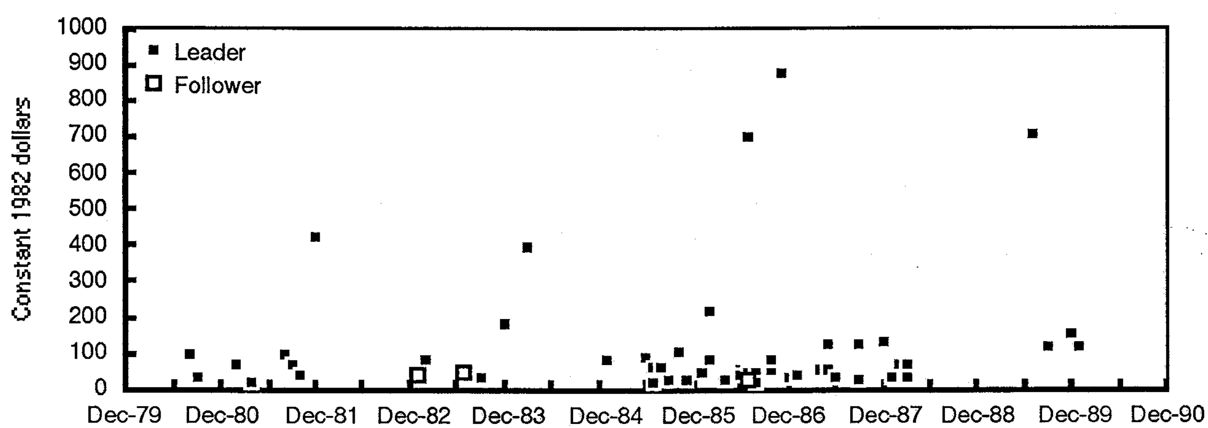

Fig. 77--Introductory prices, leaders vs. followers

Figures 78 and 79 show prices per bit. In both figures, ICs produced by firms using the follower strategy appear at the low end.

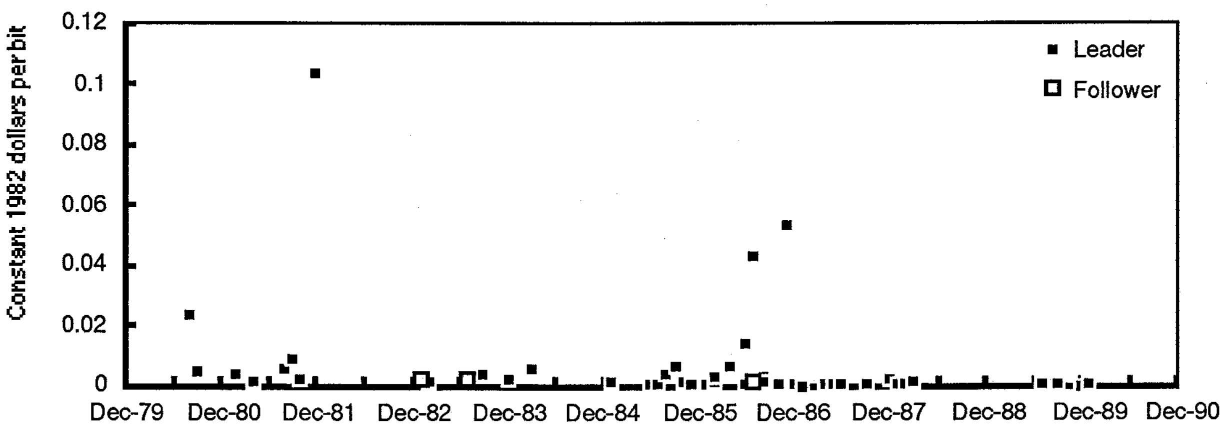

Fig. 78--SRAM prices per bit, leaders vs. followers

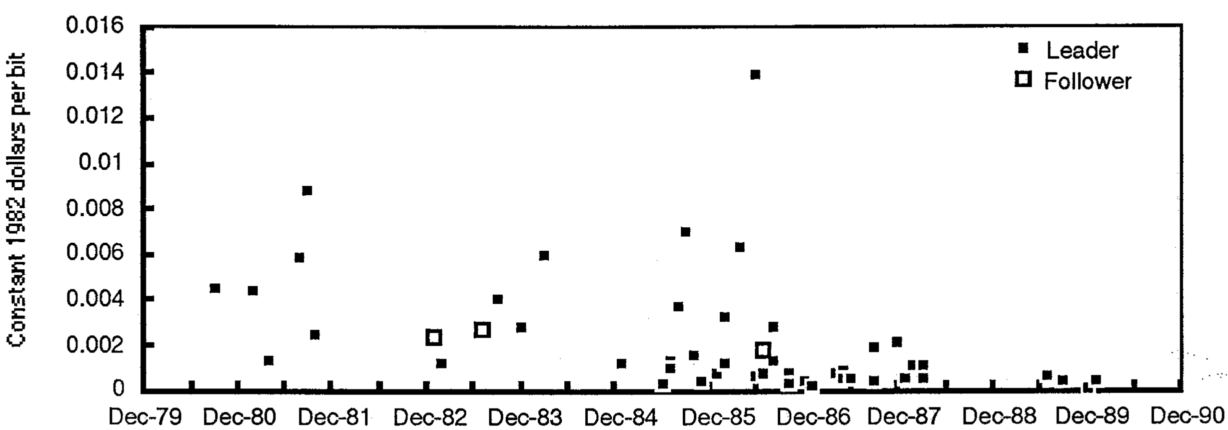

Fig. 79--SRAM prices per bit (high-priced ICs excluded), leaders vs. followers

Hypothesis 4 As It Applies to SRAMs

As in the case of systems- vs. component-oriented firms, no integrative analysis is attempted due to the lack of data on firms using technology follower strategy.

Hypothesis 4 states that the government's preference for funding advanced product R&D precludes it from taking advantage of low-cost circuits created by firms which choose the technology follower strategy. There is not sufficient data to deal with this hypothesis in the case of SRAMs. However, it appears that in cases where data are available, the hypothesis cannot be supported--followers are considerably behind the leaders, and this may not be acceptable to the government.

FINDINGS

The findings regarding SRAMs must be limited to the comparison of commercial and military ICs. Let us now summarize these finding, leaving rad-hard SRAMs for last.

If rad-hard ICs are excluded, two observations can be made. Commercial SRAMs are generally introduced a few months earlier than their military counterparts, and are generally faster and less expensive than equivalent military ICs. There appears to be little difference between the two groups of components in power dissipation or in feature sizes. It is, therefore, possible to say that commercial markets lead military markets in technology, even though the differences are not great. There is no difference in IC function or environment to account for the differences between the SRAMs produced for the two markets, although the required temperature range for military SRAMs is larger than commercial temperature range, as it is for other military ICs.

Rad-hard SRAMs are a special case. They are developed considerably later and cost considerably more than either commercial or non-rad-hard military SRAMs. There is little call for these ICs in commercial markets, and there is little data available on radiation hardness of commercial components, but this appears to be an area of greatest difference and greatest relevance to military markets.

VII. PROGRAMMABLE READ-ONLY MEMORIES

In this section we look at programmable read-only memories (ROMs). These are non-volatile memories that can retain information whether or not power is turned on. They can be programmed by the user, and the information they contain can be altered with varying degrees of difficulty, which makes programmable ROMs useful in applications in which occasional reprogramming is required. Programmable ROMs can generally be read an infinite number of times, but the number of times these ICs can be programmed is limited, but rising. Table 7.1 summarizes these properties.

Table 7.1

NON-VOLATILE MEMORY, A COMPARISON OF DEVICES

	Frequent Writes	Erasable	Erasable in system	Technology
PROM	No	No	No	Bipolar CMOS
EPROM	No	Yes	No	NMOS CMOS
EEPROM	No	Yes	Yes	NMOS (and MNOS) CMOS

SOURCE: *Electronic Design*, August 18, 1983, p. 208.

Three types of programmable ROMs are examined in this study. The first is designated as "PROM" and refers to fuse-programmable ROMs. These devices are programmed by allowing the user to burn away fuses at desired locations. Once programmed, the information in a PROM cannot be erased or altered. The second type of programmable ROM is designated as "EPROM" or "UV EPROM," electrically-programmable ROM. This type of memory device is electrically programmed by the user, and can be erased by removing the IC from the system and exposing it to ultraviolet light through quartz windows built into the IC housing. (In order to save manufacturing costs but retain the convenience of electrical programming, some suppliers offer "one-time programmable memories," EPROMs which are incorporated into housings without windows.) The information is erased from the entire chip at the same time, after which it can be programmed with fresh data. The third type of ROM is designated "EEPROM,"

electrically-erasable programmable ROM. This type of device is electrically programmed and electrically erased, usually one byte at a time. EEPROM is closer to the versatility and convenience of DRAM or SRAM than any other ROM, with the added advantage of non-volatility. A new type of EEPROM, called "flash" EEPROM, appeared on the market in 1988. A flash EEPROM is designed so that the entire chip or a sector of a chip can be quickly electrically erased at the same time.

Mask-programmable ROMs, ROMs which have information "hard-wired" into them at the time of fabrication, are not included in the study.

Several general trends have been in evidence in the programmable ROM market in the past decade.

1. Densities have increased significantly in all types of ROMs, with 4-Megabit EPROMs available in the market and 16-Megabit EPROMs in development. Both PROMs and EEPROMs have been at least a generation behind in memory capacity, but their capacities have also increased significantly during the period.
2. As densities increased, firms have made the transition from NMOS to CMOS fabrication technology.
3. As in other memory markets, prices per bit have fallen as densities have increased.
4. ROMs have moved toward greater convenience for users, such as easier erasure, and shorter write times.

CLASSIFYING FIRMS

The firms whose products are included in the study database are shown in Table 7.2, together with the classification in accordance with the nomenclature of Section II. While ROM was included on some of the VHSIC ICs, separate programmable ROM chips were not fabricated during the program. Although the military has had requirements for EEPROMs, there has been no military funding specifically directed for the development of these ICs,[1] and limited funding for rad-hard EEPROMs past the 256-kbit level.[2] (Other types of non-volatile memory are being funded by the military.)

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[1]R. Fedorak, "Information Storage And Retrieval Overview," presented at the meeting of the Advisory Group on Electron Devices (AGED) Special Technology Area Review (STAR) on Nonvolatile Memory Technologies, National Bureau of Standards, Boulder, Colorado, 23 June 1988.

[2]R.L. Wiker, "NVSM Circuit Trends," AGED STAR, 1988.

Table 7.2

CLASSIFICATION OF PROM PRODUCERS

Firm Name	Commercial or Military	Systems or Components	Leader or Follower
AMD	C, M	Co	L
Catalyst Semi.	C	Co	F
Cypress	C, M	Co	L
Exel	C	Co	L
Fairchild	C	Co	L
Fujitsu	C	Co	L
General Instr.	C	S	L
Harris	C, M	Co	L
Hitachi	C	Co	L
Hughes	C, M	S	L
Inmos	C	Co	L
Intel	C, M	Co	L
Int'l CMOS Tech.	C	Co	L
Intersil	C	Co	L
Mitsubishi	C	Co	F
Monolithic Mem.	C	Co	L
Motorola	C	Co	L
National Semi	C	Co	L
NCR	C, M	S	L
NEC	C	Co	L
Oki Semi.	C	Co	L
Philips/ Signetics	C	Co	L
Raytheon	C	S	L
Rockwell	C	S	F
RCA	C	S	L
Seeq	C, M	Co	L
Thomson-CSF	C	S	L
TI	C, M	Co	L
Toshiba	C	Co	L
VLSI Tech.	C	Co	L
WaferScale	C	Co	L
White Tech.	C	Co	L
Xicor	C	Co	L

U.S. firms have been leaders in non-volatile technology, and have invested heavily to maintain the lead because of the technology's relevance to microprocessors, digital signal processors, gate arrays, and application-specific ICs. Among U.S. firms, Seeq has been a leader, the first firm to introduce "flash" EEPROMs. Other firms which have been prominent in the market have been Intel and Xicor. Although Japanese firms have had a

significant presence in the market, they have not dominated the programmable ROM market to the same extent as other memory markets.

PRODUCT EVALUATION

Before proceeding to product evaluations, let us review the last decade of development in programmable ROMs. The changes which have taken place in memory capacities over the past ten years are shown in Figure 80 for different types of ROMs. UV-EPROMs, with their one-transistor cells, have traditionally had the highest bit-counts, followed by PROMs and EEPROMs. As their densities increased, EPROMs and EEPROMs have become increasingly popular because they provide flexibility of alterable memory with the advantages of non-volatility.

In 1980 the market was dominated by 64-kbit EPROMs, which were moving from NMOS to CMOS manufacturing technology. Both power dissipation and programming voltages were starting to fall with the transition to finer design rules. 16-kbit EEPROMs became available on the market from Hitachi and Intel, with several other firms preparing to enter the market at these levels. As in the case of SRAMs, research on programmable ROM technologies has been well-represented at ISSCC. In 1980, Texas Instruments introduced a 128-kbit UV-EPROM, which had a fast access speed of 200 ns and used 3.5-μm design rules.

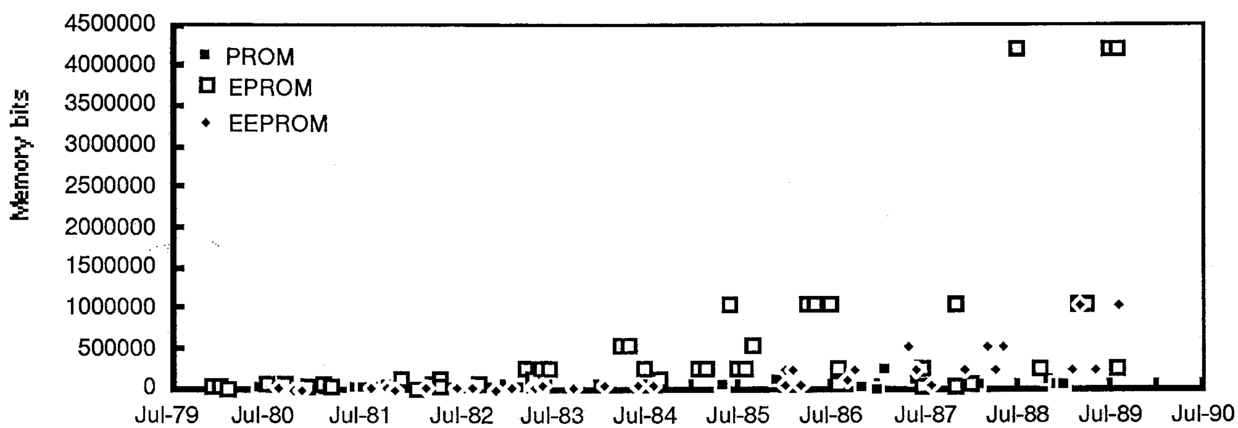

Fig. 80--ROM bit count by memory type

At the 1983 ISSCC, PROMs hit 64-kbit densities for the first time. EEPROMs also reached 64-kbit densities. Although the majority of EEPROMs were still

programmed with higher voltage than the voltage used for reading data (usually 20 V to 25 V for writing and 5 V for reading), Intel introduced a 16-kbit EEPROM which used 5 V for both reading and writing data. 256-kbit EPROMs were introduced by Intel and Fujitsu. In 1984, Intel and AMD had commercial 512-kbit EPROMs. One-time programmable memories, EPROMs without windows, have become popular as plastic packaging made them competitive with mask-programmable ROMs in terms of cost, reliability, and testing.

At the 1985 ISSCC, Intel introduced a 256-kbit EPROM with row and column redundancies for improved yield. At the same meeting, Hitachi and Toshiba introduced 1-Mbit EPROMs with access times as fast as 80 ns. EEPROMs were featured at the 64-kbit level, although Toshiba had introduced a 256-kbit EEPROM.

In 1987, several companies, including Intel and Texas Instruments, entered the market with 1-Mbit UV EPROMs. The first 4-Mbit UV EPROM was introduced by Toshiba at that year's ISSCC. CMOS EEPROMs at 256-kbit levels were introduced by Seeq at the same meeting, as were 128-kbit EEPROMs with the flash erase feature.

The following year, Intel introduced 4-Mbit EPROMs into production, using its well-understood and tested 1-μm process. The biggest market development in 1988, however, was the introduction of flash EEPROMs, with Seeq's chip being first to market. 256-kbit EEPROMs, with and without flash erase, were prominently featured at the 1988 ISSCC.

With this brief overview in place, let us now proceed to the evaluation of PROMs along five characteristics: memory capacity (number of memory bits), access time, feature size, power dissipation, and price (both introductory price and introductory price per bit).

Commercial vs. Military

The charts below compare commercial and military programmable ROMs. In most cases, all categories of ROMs are combined into a single chart, except when there are specific reasons to separate them. The distribution of commercial and military data points among different ROM types is shown in Figure 81 below.

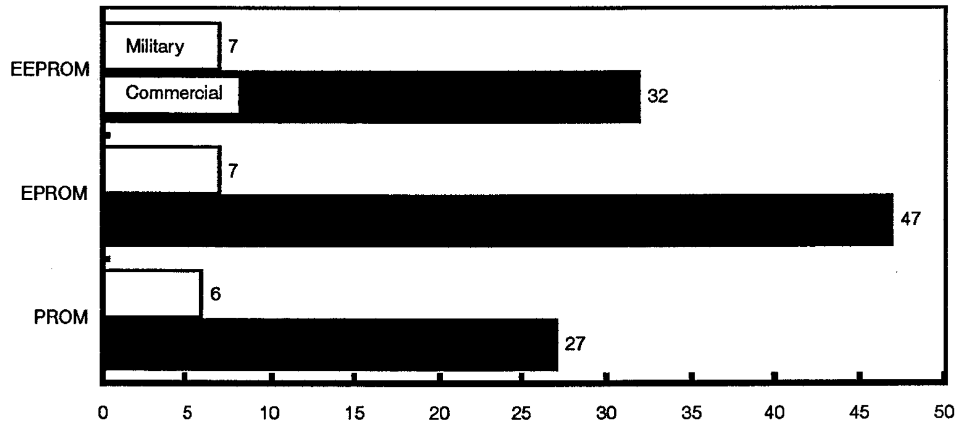

Fig. 81--ROM data point counts by type, commercial vs. military

Memory Capacity

Figure 80 showed the changes in memory capacity over time by ROM type. Figures 82 through 84, below, show a comparison of memory capacity for military and commercial ROMs for each type of ROM separately. The scales of the charts are different, reflecting different levels of development in different types of ROMs. Commercial markets have led ROM density in every category, with the exception of the 32-kbit EEPROM introduced by NCR in July 1981, shown in Figure 84.

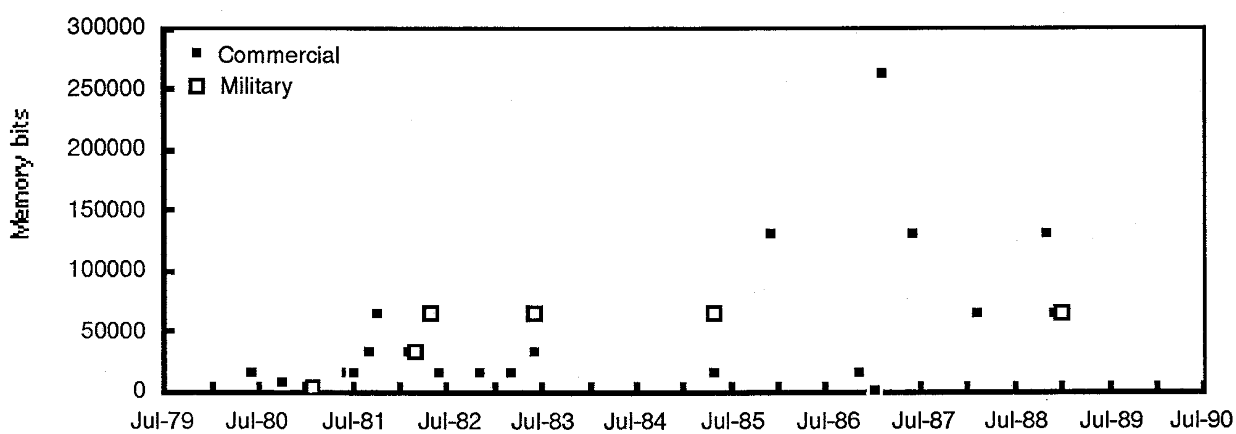

Fig. 82--PROM capacity, commercial vs. military

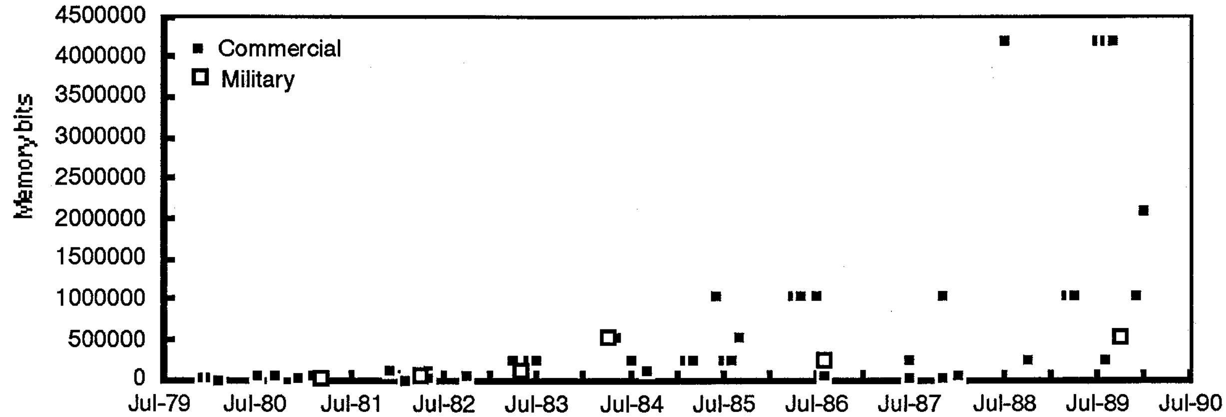

Fig. 83--EPROM bit counts, commercial vs. military

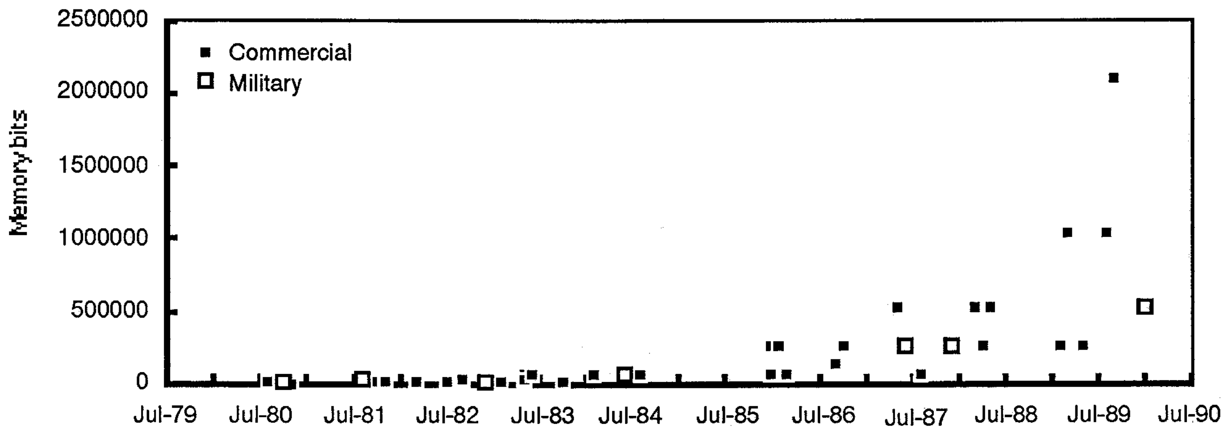

Fig. 84--EEPROM bit counts, commercial vs. military

Access Time

Access times for different types of ROMs by memory type are shown in Figure 85. PROMs are the fastest of the three because they are mainly manufactured with bipolar technology; EPROM and EEPROM access times appear to be randomly intermixed. As

may be expected, all access times show a general downward trend with advances in technology.

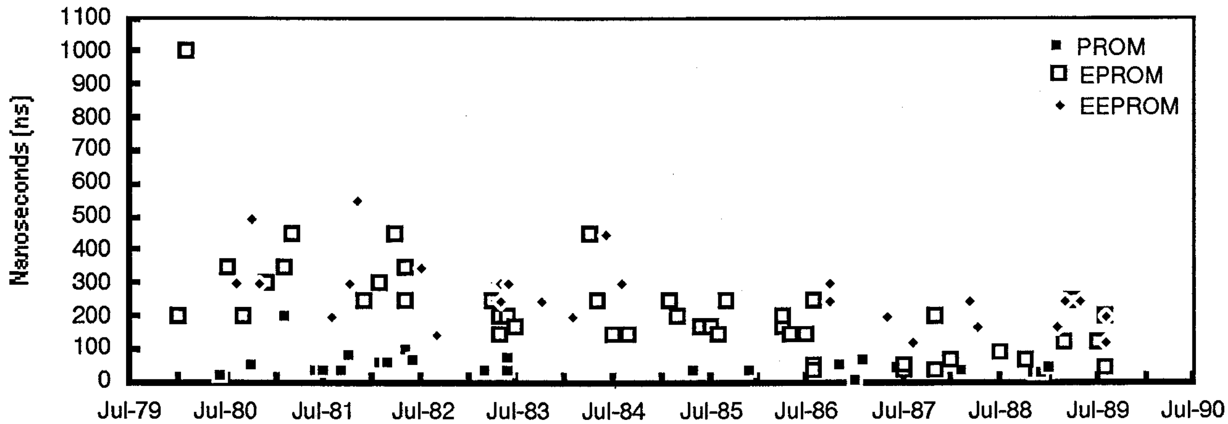

Fig. 85--ROM access times by memory type

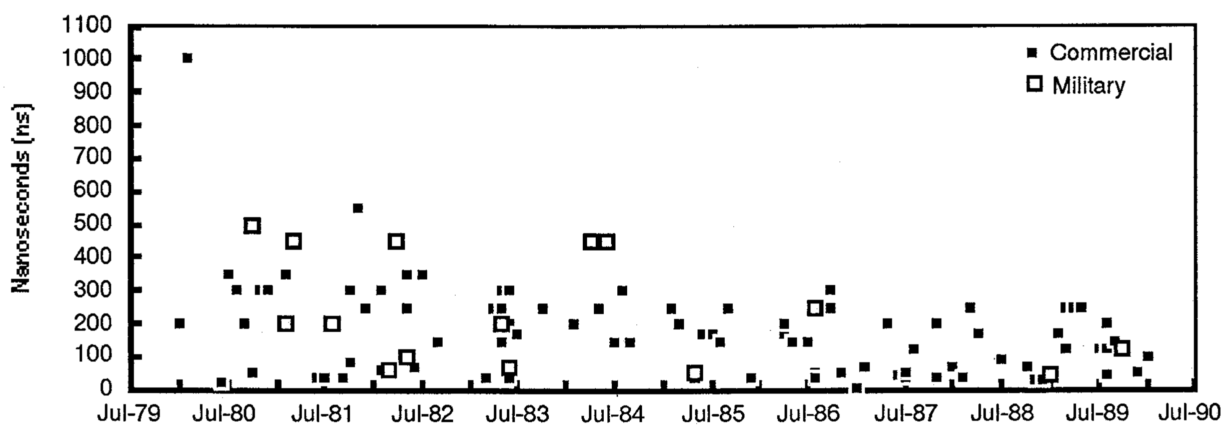

Fig. 86--ROM access times, commercial vs. military

Access times for all ROMs are presented in a single chart (Fig. 86) because this is one of the parameters on which different types of memory compete with each other. The range of access times is not very wide. There appears to be little difference between commercial and military ROMs, which are interspersed quite randomly throughout the

commercial data points. Neither commercial nor military access times appear to have taken sudden jumps during the decade under analysis.

Feature Size

Figure 87 shows ROM feature sizes. Although there is comparatively little data on feature sizes used for military ROMs, the data points which appear in the chart give no indication that the military has led the commercial market in this dimension, even during the time when the results of the VHSIC Program were being introduced into the market during the mid-1980s. The reason for this may be the absence of programmable ROM chips from the "menu" of chips produced for the VHSIC Program.

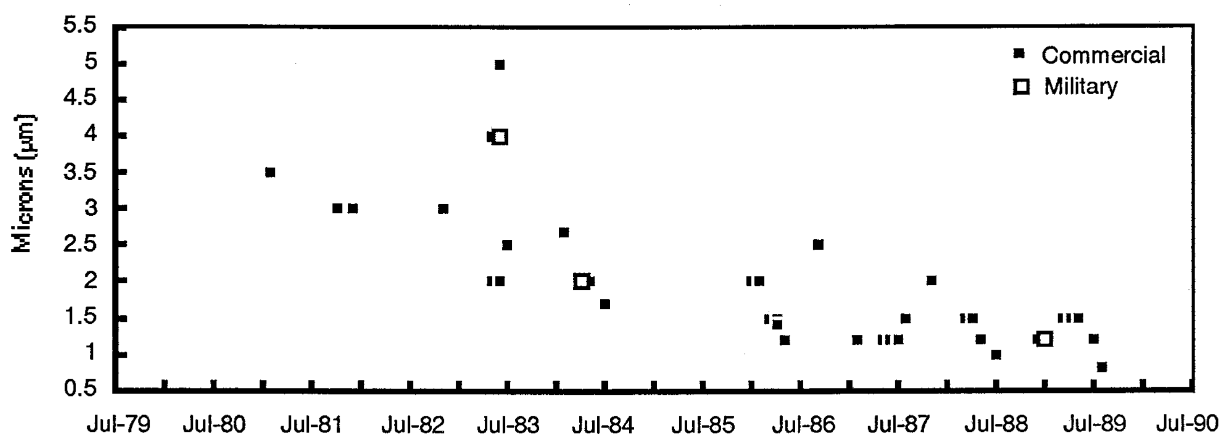

Fig. 87--ROM feature sizes, commercial vs. military

Power Dissipation

ROM power dissipation as a function of IC capacity is shown in Figure 88. This breakdown is presented to demonstrate that military and commercial power dissipation levels can be compared without a breakdown by ROM type. The figure shows that there is not a great deal of difference in power dissipation between different types of ROMs at various IC capacity levels. PROMs generally, but not always, have highest dissipation levels; EPROMs and EEPROMs are distributed throughout the range.

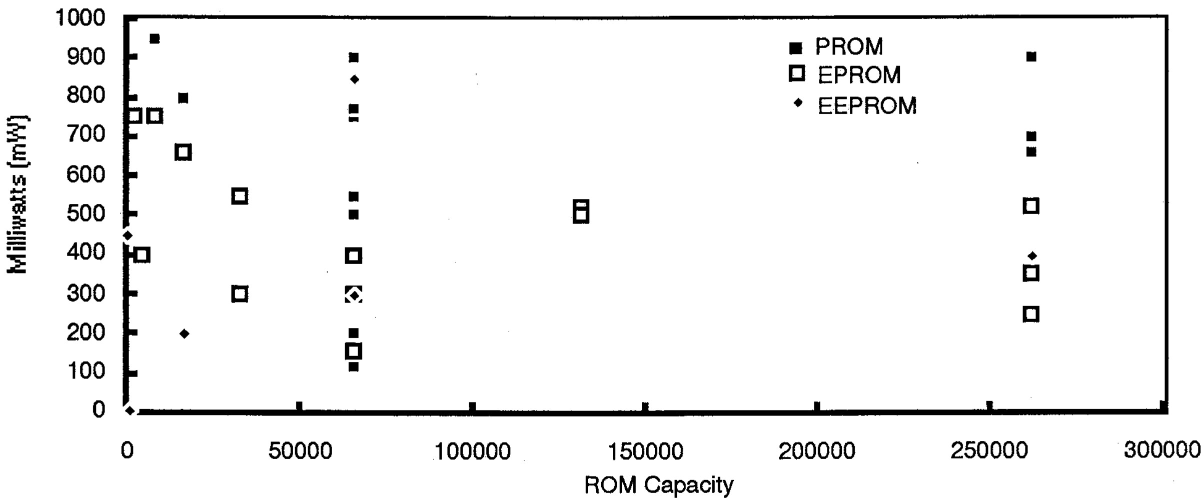

Fig. 88--ROM power dissipation by IC capacity

Figure 89 presents a comparison of power dissipation in commercial and military ROMs. There is a limited number of military data points, but the data points that are available appear to be evenly distributed, with military ROMs appearing at both the low and the high ends of the power dissipation range.

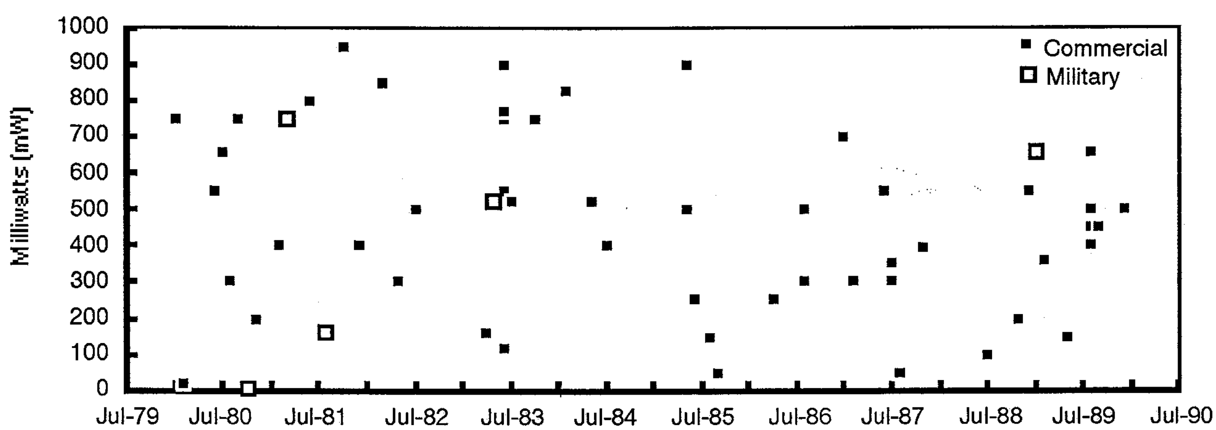

Fig. 89--ROM power dissipation, commercial vs. military

Price

Figure 90 presents information on introductory prices for different types of ROMs. A change in the relative prices of the three types of ROMs appears to have taken place in the middle of the decade. In the early part of the 1980s, PROMs were the least expensive of the group, followed by EEPROMs. EPROMs were the most expensive. However, as discussed above, EPROMs also led other types of ROMs in capacity by at least one generation at any given time. It is, therefore, likely that higher memory capacity accounts for the high price of EPROMs.

However, recently EEPROMs have become more expensive than other types of programmable ROMs. As the next figure will show, the high introductory prices on EEPROMs stem mainly from the increase in EEPROM densities. Prices per bit, which exclude the effect of memory capacity, are presented in Figure 91.

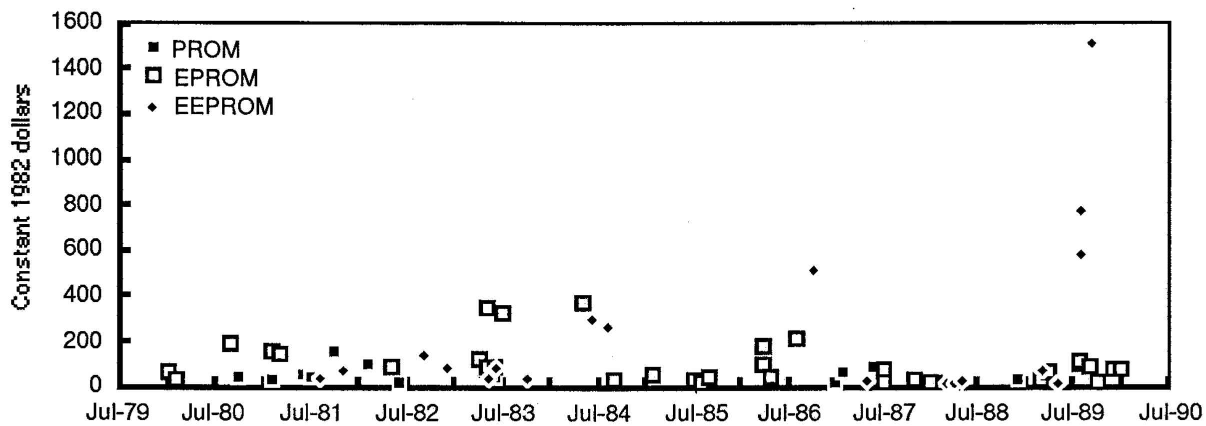

Fig. 90--ROM introductory prices by memory type

Figure 91 indicates that when capacity is taken into account, EPROMs have been the least expensive of the three types of ROMs throughout the time period in this study. PROM and EEPROM per bit prices are about the same, both more expensive than EPROMs. (Figure 92 presents greater detail on lower-cost ROMs which are crowded together along the horizontal axis in Figure 91.) The high-capacity EEPROMs which appear as outliers in Figure 90 show up as being in line with other programmable ROM prices per bit.

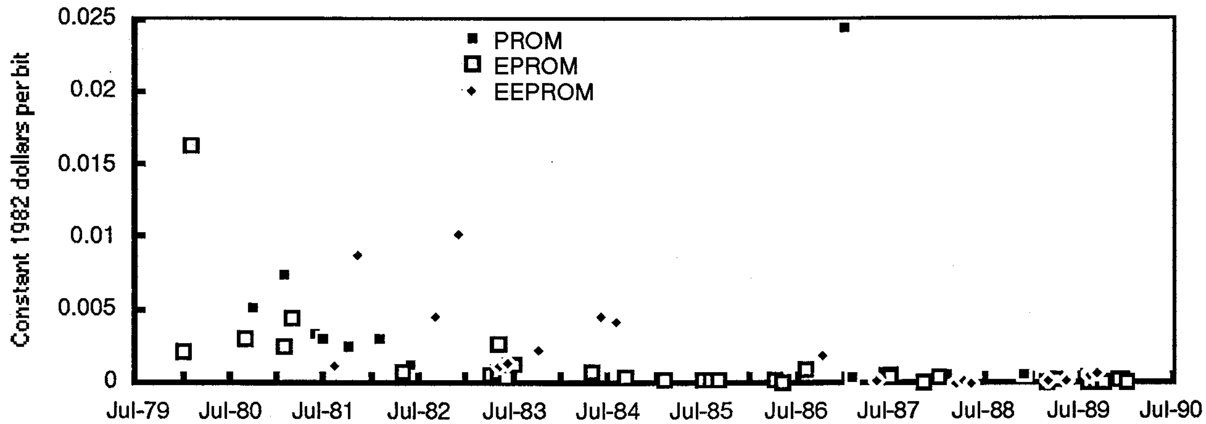

Fig. 91--ROM introductory prices per bit by memory type

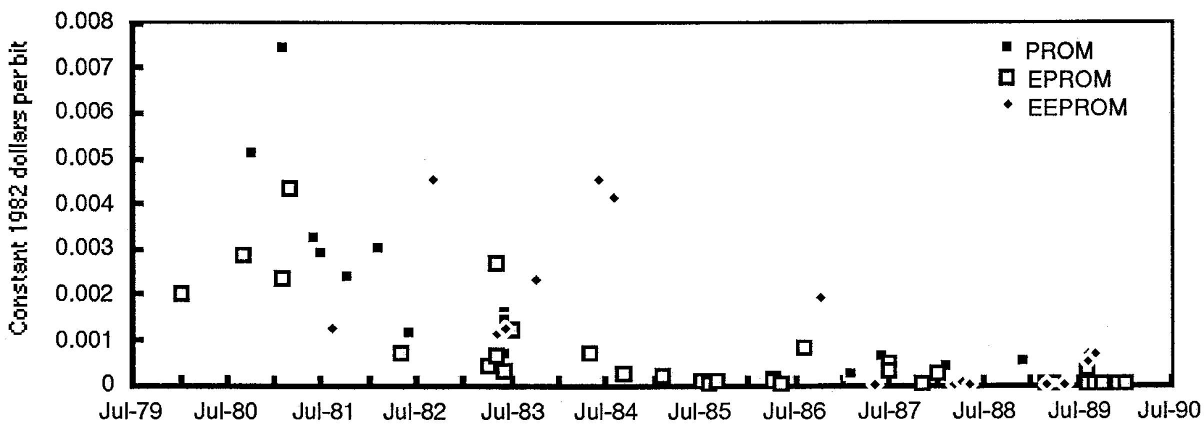

Fig. 92--ROM prices per bit by memory type, lower price range

Let us now turn to a comparison of prices for commercial and military ROMs, starting with introductory prices, shown in Figure 93. Prices for military ICs are higher than prices for commercial ICs during the period 1983 to 1985, but otherwise comparable. No data on military PROMs are included in the data base; the available information is evenly distributed between EPROMs and EEPROMs. Since military EPROMs and EEPROMs run behind their commercial counterparts in densities, density cannot provide the explanation for greater price of military ROMs.

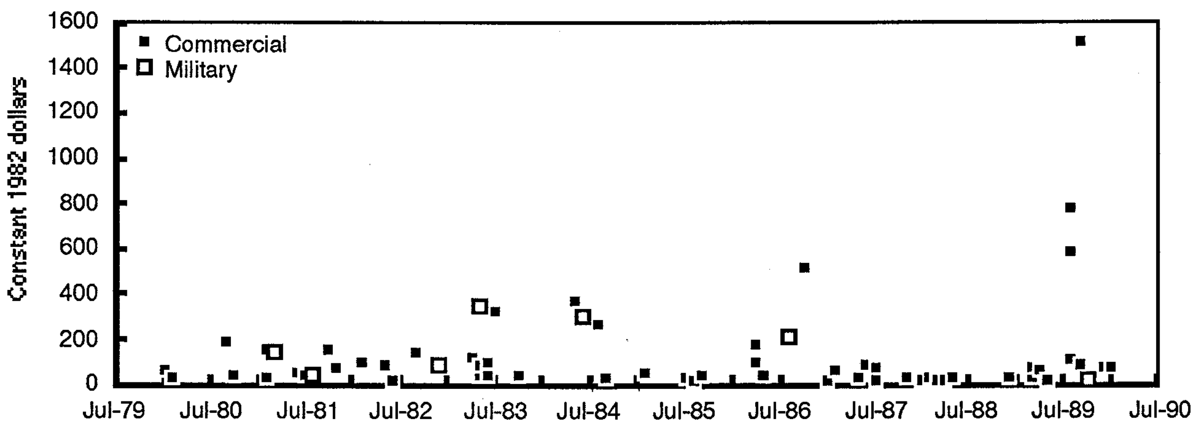

Fig. 93--ROM introductory prices, commercial vs. military

Finally, Figure 94 presents a comparison of prices per bit for commercial and military ROMs. Although this was not obvious from the previous figure, military ROMs are more expensive than their commercial counterparts when capacity is taken into account. In most cases the differences are quite small, however, with military data points falling either within the range of commercial points or just outside.

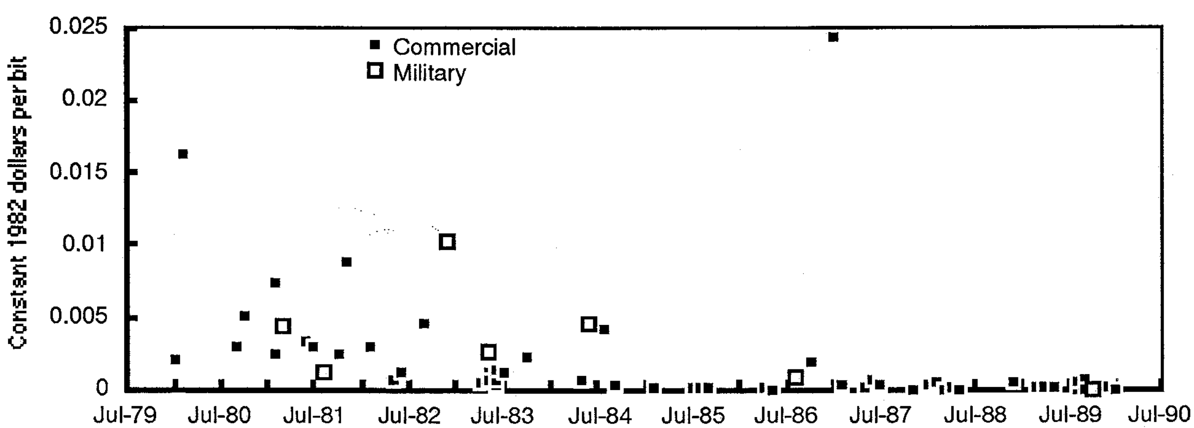

Fig. 94--ROM prices per bit, commercial vs. military

Integration of Multiple Characteristics

In order to understand whether suppliers of commercial and military ROMs make different trade-offs between various IC characteristics, a regression analysis was performed relating different ROM characteristics to the time of introduction. The results of this analysis is presented in Table 7.3.

All variables in regression 1 are significant, and none of the dummies is included. Signs on two of the variables are as expected: negative on "Access Time" (i.e., faster ROMs are introduced later than slower ones) and positive on "Ln No. of Bits" (i.e., higher memory capacities introduced later). However, the sign on "Price per bit" is positive, which is in conflict with the picture of the data as presented in Figures 91 and 94 above. This peculiarity was also present in regression 2, in which the military dummy was included. The dummy was not significant, and, indeed, reduced the fit of the regression to the data as measured by Adjusted R^2.

In an attempt to explore further the reasons for the strange sign of "Price per bit," an interactive relationship was established between this variable and "Ln No. of Bits." Figures 91 and 94 indicate that price per bit dropped with time, i.e., price per bit has fallen as the number of bits on a single chip has risen. It is, therefore, not surprising that there is a relationship between the cost of ROMs and their memory capacity. When this relationship is taken into account in the regression through the use of an interactive term, the fit to the data improves significantly. The negative sign of the interactive variable also means that the positive sign on the "Price per bit" variable does not imply an increasing price per bit over time--price per bit depends on the density of the IC, and there is an inverse relationship between density and price per bit.

Since "Access Time" is no longer significant when the interaction of "Price per bit" and "Ln. No. of Bits" is taken into account, it is dropped from regression 4. The best fit to the data is found in regression 5 in which a military dummy is added to the variables of regression 4. Although the dummy itself is not significant at the 10% level, it contributes information to the regression, as evidenced by the increase in Adjusted R^2.

Hypothesis 1 As It Applies to Programmable ROMs

Hypothesis 1 states that commercial markets can be expected to be on par with or lead military markets in technology. The data indicate that military programmable ROMs lag their commercial counterparts somewhat, but the difference is slight and not statistically significant. Hypothesis 1 is supported by data in the programmable ROM market.

Table 7.3

REGRESSION RESULTS--COMMERCIAL VS. MILITARY ROMS

Variables	Regression 1	Regression 2	Regression 3	Regression 4	Regression 5
Constant	- 68.597 (0.020)	- 68.626 (0.021)	- 36.091 (0.222)	- 34.473 (0.231)	- 30.933 (0.278)
Access time	- 0.072 (0.001)	- 0.062 (0.004)	- 0.029 (0.173)		
Ln No. memory bits	20.243 (0.000)	20.245 (0.000)	18.623 (0.000)	18.268 (0.000)	18.069 (0.000)
Price per bit ($82)	4170.249 (0.000)	4171.469 (0.001)	20873.877 (0.000)	21679.545 (0.000)	24337.958 (0.000)
$/bit*Ln No. memory bits			-2454.926 (0.000)	-2610.581 (0.000)	-2995.309 (0.000)
Military dummy		0.144 (0.989)			14.228 (0.123)
EPROM dummy			- 17.591 (0.004)	- 20.047 (0.001)	- 21.513 (0.000)
Adjusted R^2	0.605	0.598	0.688	0.686	0.693

NOTE: Numbers in parentheses represent the significance level of the coefficient, i.e., 0.010 means that the coefficient is significant at the 1% level.

Generation Skipping

As discussed above, differences between commercial and military ROMs exist, but are not significant either in individual parameters or in integrative analysis. Additionally, there is no indication that either commercial or military ROMs skipped generations. All IC characteristics examined show a gradual progress. Even the introduction of a new kind of programmable ROM, the flash EPROM, did not alter the pattern for any IC characteristic. It is, therefore, possible to say that there is support for Hypothesis 2 in the programmable ROM market.

Systems vs. Components

Let us now turn to the examination of ROMs produced by systems- and component-oriented firms. Systems firms are represented in the data base, but to a different extent in different types of ROMs. Figure 95 shows the distribution of data points between systems- and component-oriented firms. There are fewer points for systems-oriented firms than for component-oriented firms in every category. The majority of these are concentrated in EEPROMs, and, given the differences which exist in several features between EEPROMs and other types of ROMs, some of the differences between systems- and component-oriented firms can be attributed to the difference in the distribution of data points in the data base. With this in mind, let us now proceed to examine IC characteristics.

Memory Capacity

Figure 96 shows the memory capacity of different types of ROMs produced by systems- and component-oriented firms. The figure indicates that ROMs produced by systems-oriented firms are of lower capacities than those produced by component-oriented firms. In part, this can be explained by the concentration of systems-oriented data points in EEPROMs which are not available in densities as high as EPROMs (see Fig. 80). However, this does not account for the entire difference, since ROMs produced by systems-oriented firms appear to be of consistently lower densities than those produced by component-oriented firms.

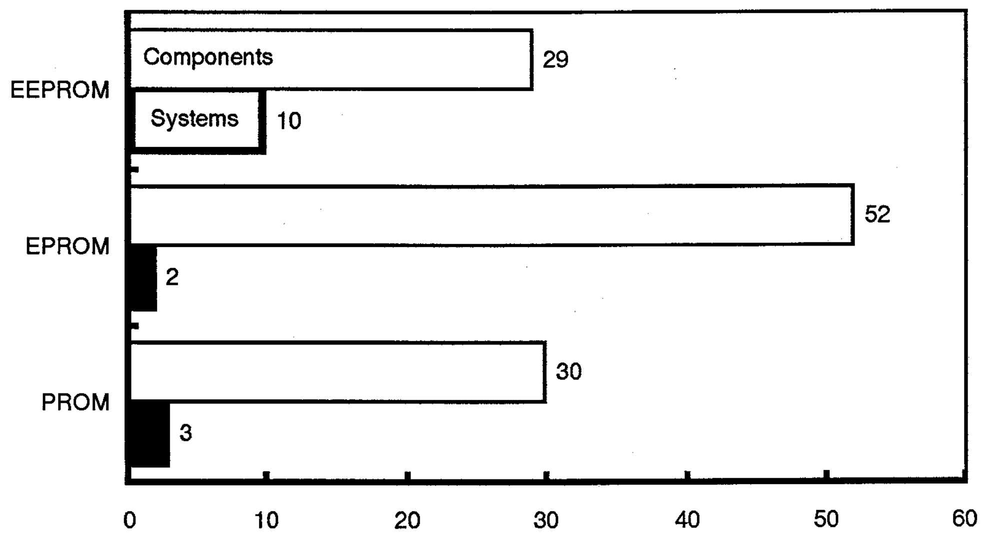

Fig. 95--ROM data point counts by type, systems- vs. component-oriented firms

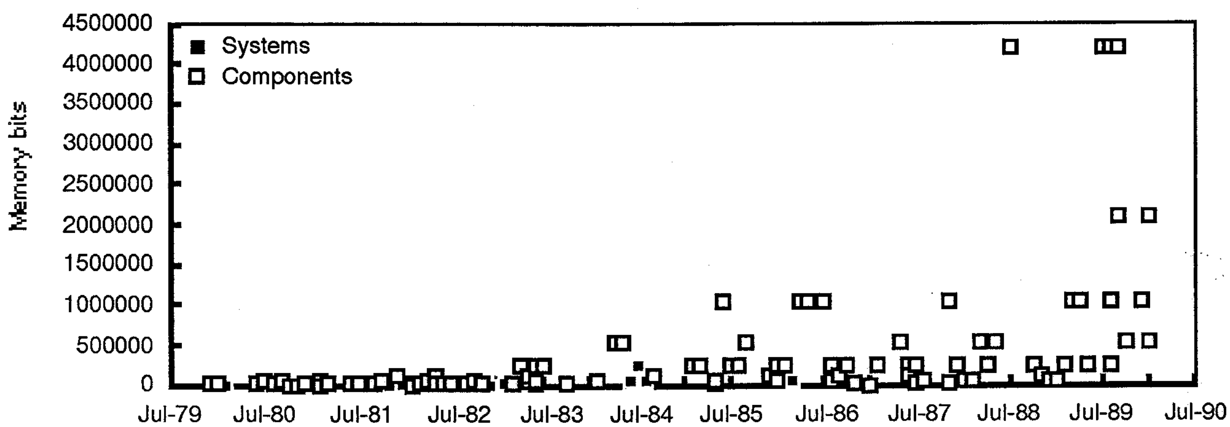

Fig. 96--ROM capacity, systems- vs. component-oriented firms

Access Time

Access times for various types of programmable ROMs are shown in Figure 97. ROMs produced by systems-oriented firms have longer access times than ROMs produced by component-oriented firms. Part of the difference is due to the concentration of data points attributable to systems-oriented firms in EEPROMs--as shown in Figure 85 above, EEPROMs have the longest access times of the three types of ROMs in this study. Few PROMs in the data base are produced by systems-oriented firms, which also contributes to longer access times for ICs produced by these firms.

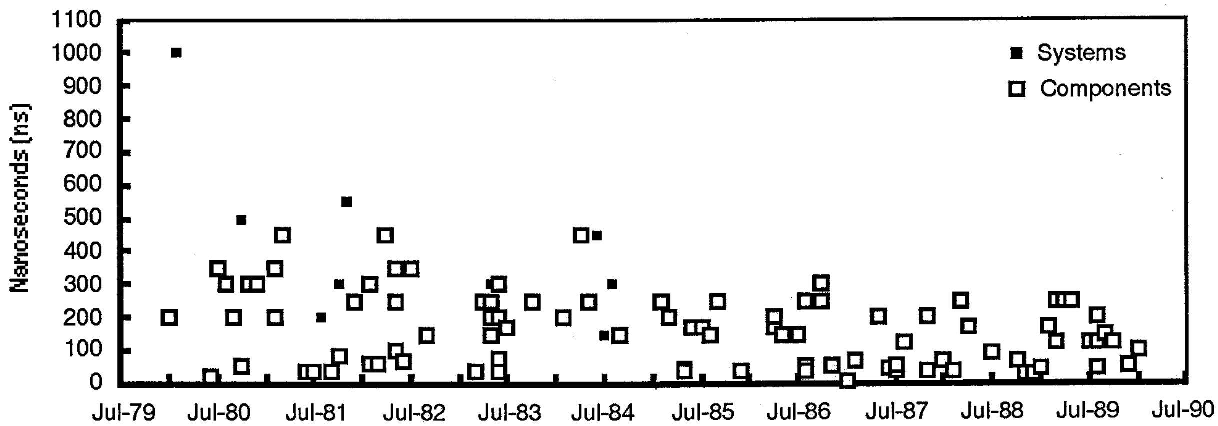

Fig. 97--ROM access times, systems- vs. component-oriented firms

Feature Size

Feature sizes are compared in Figure 98. Little information is available for ROMs produced by systems-oriented firms, but the data points that are available do not indicate a significant difference between systems- and component-oriented firms along this dimension.

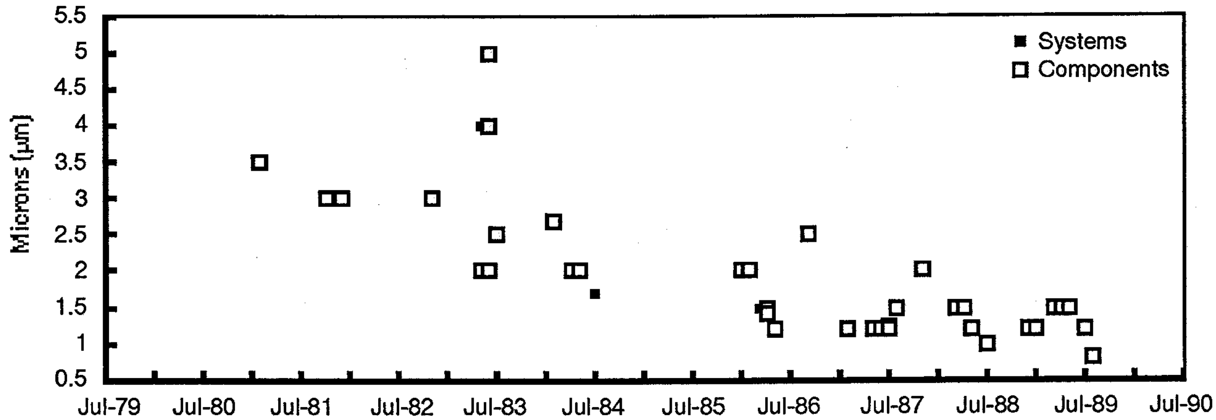

Fig. 98--ROM feature sizes, systems- vs. component-oriented firms

Power Dissipation

Figure 99 shows data on power dissipation for ROMs produced by systems- and component-oriented firms. Data on systems-oriented firms are very limited, but the available data points indicate that the power dissipation for ICs produced by these firms is generally lower than that of the ICs produced by component-oriented firms. As shown in Figure 88, EEPROMs do not have significantly lower power dissipation than other memory types of equivalent capacity, so the predominance of EEPROMs among systems-oriented data points cannot account for the difference.

There is not enough data to use as a basis for analysis, but it is conceivable that systems-orientation is responsible for the difference along this dimension. The logic would be as follows. A system integrator has to worry not only about IC performance, but also about the way the heat generated by the IC will be removed from the system. Lower power dissipation may lower the overall system cost by reducing the need for cooling fans and other cooling equipment.

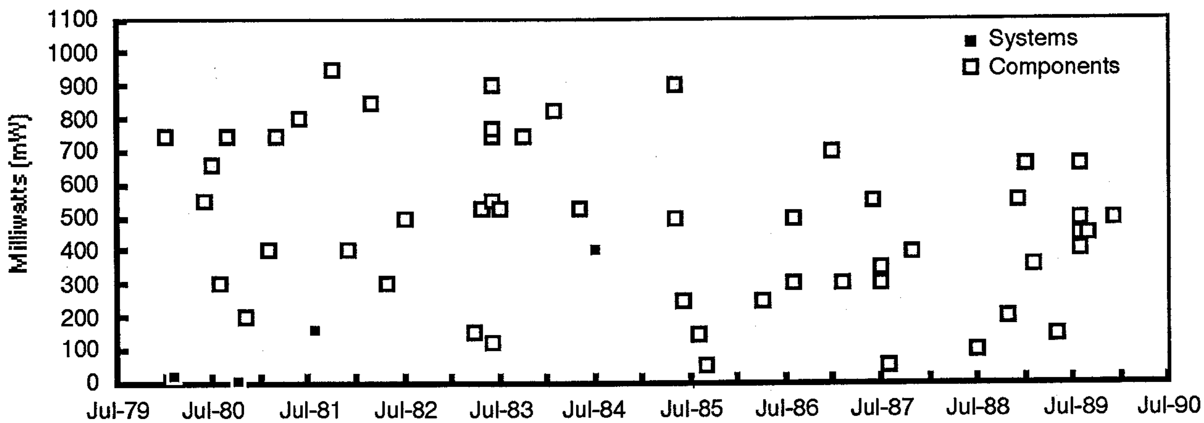

Fig. 99--ROM power dissipation, systems- vs. component-oriented firms

Price

Figure 100 shows introductory prices for ROMs produced by systems- and component-oriented firms. The figure indicates that ICs introduced by systems-oriented firms are generally priced lower than those produced by component-oriented firms. However, part of the reason for this may be the predominance of EEPROMs among the systems-oriented data points and the lower capacity of these ICs.

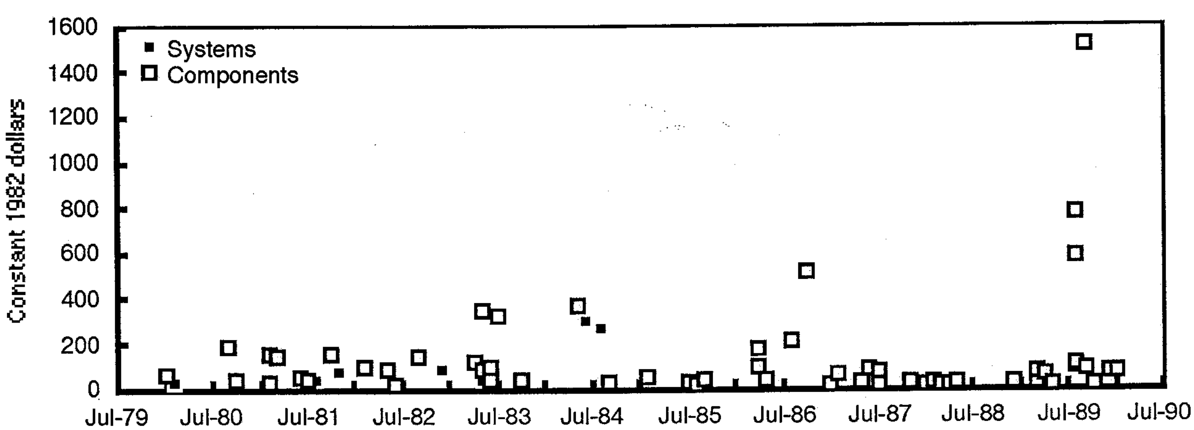

Fig. 100--ROM introductory prices, systems- vs. component-oriented firms

Differences in capacity are taken into account in Figure 101, which shows ROM prices per bit. With the exception of Motorola's MCM10149 PROM, ICs introduced by systems-oriented firms are higher-priced per bit than those introduced by component-oriented firms. It does appear that the differences in introductory prices shown in the previous figure are due to the predominance of EEPROMs among systems-oriented data points. These ICs are lower in price at the time of introduction because their densities are lower than densities of ICs produced by component-oriented firms.

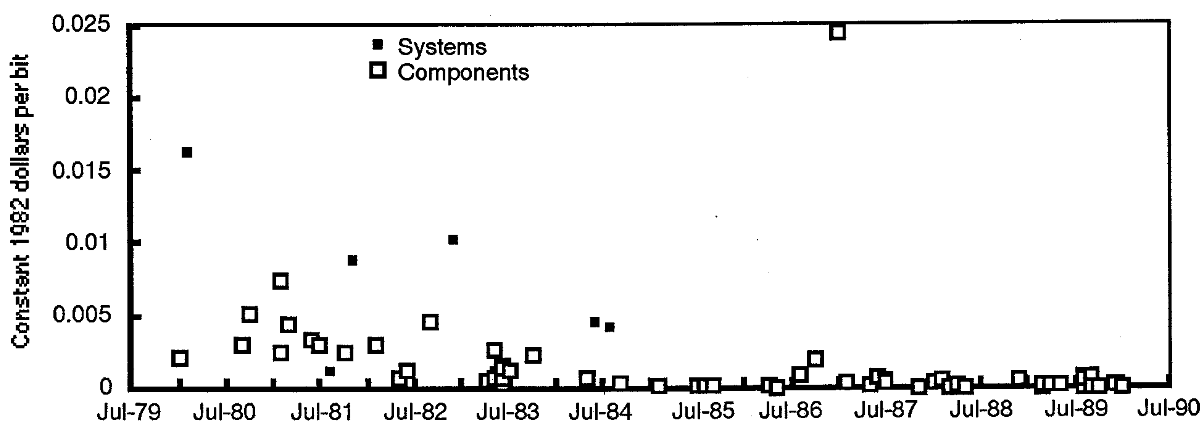

Fig. 101--ROM prices per bit, systems- vs. component-oriented firms

Integration of Multiple Characteristics

In order to determine whether systems- and component-oriented firms perform different trade-offs in the introduction of ROMs, a multivariate regression analysis was performed. The results of this analysis are presented in Table 7.4. The "Systems" dummy is not statistically significant in any of the regressions. Although the result cannot be stated categorically due to comparative scarcity of systems-oriented data in the data base, it appears that the differences in the time of introduction of ROMs by systems- and component-oriented firms are not statistically significant.

Table 7.4

REGRESSION RESULTS--ROMS PRODUCED BY SYSTEMS- VS. COMPONENT-ORIENTED FIRMS

Variables	Regression 6	Regression 7	Regression 8
Constant	- 76.081 (0.011)	- 85.771 (0.005)	- 33.768 (0.244)
Access time	- 0.090 (0.001)	- 0.075 (0.007)	
Ln No. memory bits	21.025 (0.000)	22.120 (0.000)	18.244 (0.000)
Price per bit ($82)	4239.476 (0.000)	4259.767 (0.000)	22452.758 (0.000)
$/bit*Ln memory capacity			-2735.396 (0.000)
Systems dummy	16.845 (0.207)	10.055 (0.464)	5.053 (0.621)
EPROM dummy		- 11.149 (0.099)	- 19.838 (0.001)
Adjusted R^2	0.609	0.620	0.682

NOTE: Numbers in parentheses show the significance level of the coefficient.

Although the variable "Access Time" is significant in regression 7, it is dropped in regression 8. When it is added to the variables in this regression, it is not significant and reduces the fit to the data.

Hypothesis 3 As It Applies to Programmable ROMs

Hypothesis 3 stated that component-oriented firms can be expected to introduce technological advances before systems-oriented firms. There is relatively little data on ROMs introduced by systems-oriented firms. However, the data that are available indicate that there is not a great deal of difference between ROMs introduced by two types of firms. There is no support for the hypothesis in the data.

Leader vs. Follower

As noted at the start of the section, the database contains almost no information about ROMs produced by firms using the follower strategy in the market. Figure 102 shows the breakdown of available data points among different ROM types.

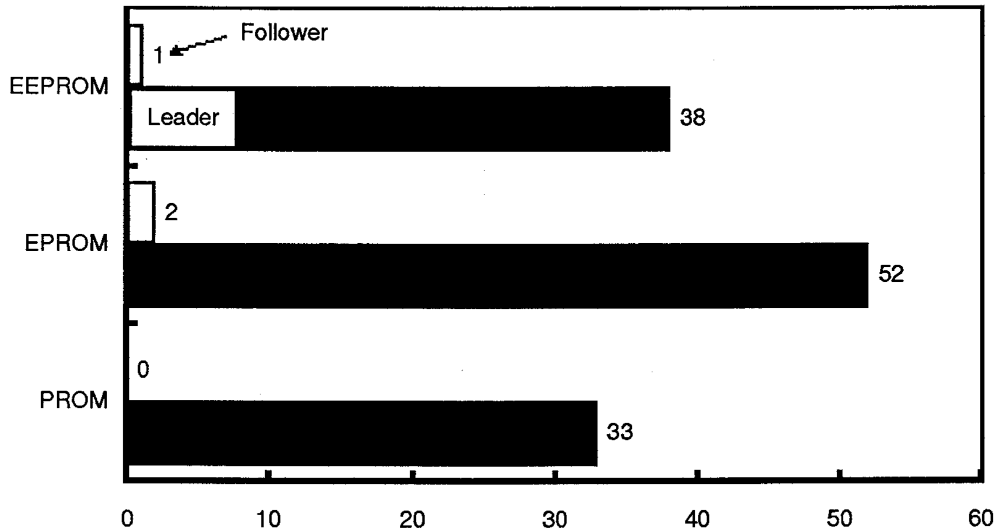

Fig. 102--ROM counts by type, leaders vs. followers

Although the picture presented above is bad enough, in some cases only partial data are available about particular ICs in the data base, so information about some follower characteristics is completely unavailable. For this reason, it is not possible to provide analysis of ROMs along this dimension. The figures showing available data are below.

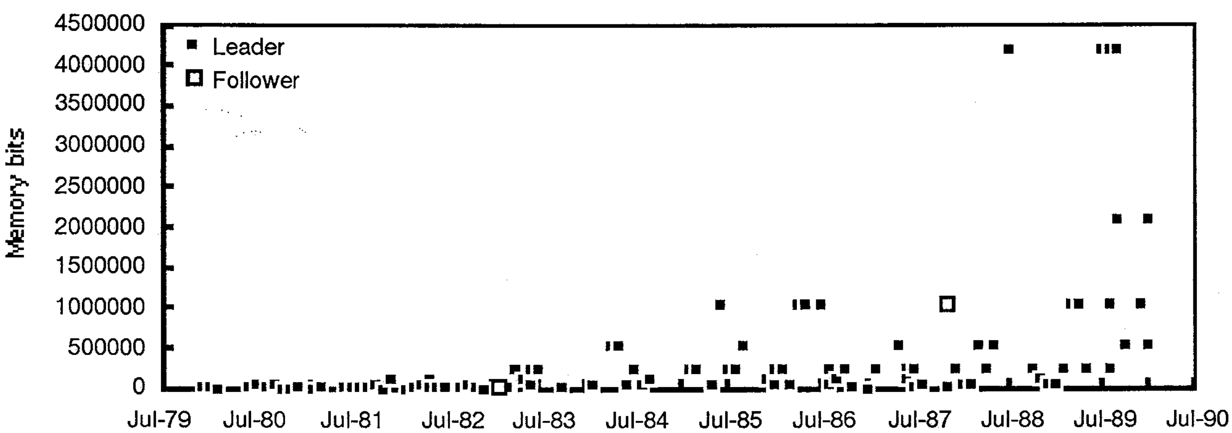

Fig. 103--ROM capacity, leaders vs. followers

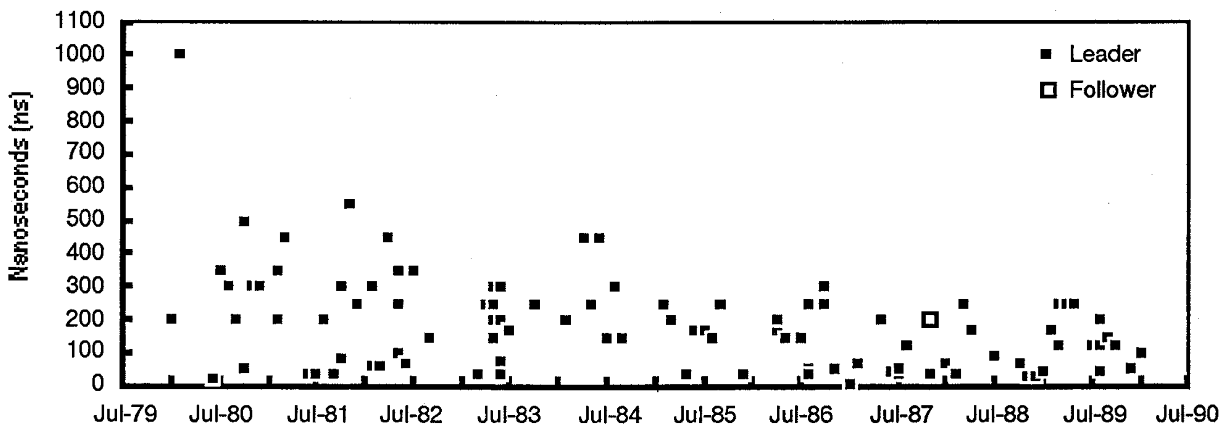

Fig. 104--ROM access times, leaders vs. followers

FINDINGS

Three of the four hypotheses advanced in Section II were tested for programmable ROMs. The data were insufficient to test the hypothesis about technology leaders and followers.

As pointed out in the discussion of commercial and military ROMs, there is some indication that military programmable ROMs lag their commercial counterparts; this lag is not substantiated by statistical analysis. Given the limited funding committed by the military to this class of ICs, it is interesting that the military and commercial ROMs are as similar as they are.

Hypothesis 2, dealing with generation skipping, can be supported by the data. Both commercial and military ROMs showed smooth progress along all IC characteristics.

There does not seem to be very much difference between ROMs produced by systems- and component-oriented firms. For the most part, component-oriented firms lead along various IC characteristics, but ROMs produced by systems-oriented firms have lower power dissipation. The differences between ROMs produced by systems- and component-oriented firms are not statistically significant, however.

Although there is demand for nonvolatile memory in a number of military applications, the majority of military funding has been concentrated in areas other than

silicon programmable ROMs. In view of this, it is interesting to see that military programmable ROMs are not very far behind their commercial counterparts, certainly not far enough to be picked up by statistical analysis.

VIII. CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the findings on individual component groups and presents the conclusions of the study. It also develops some recommendations in light of these conclusions.

SUMMARY OF RESULTS

The hypotheses advanced in Section II are restated below, together with the findings from individual component Sections.

> Hypothesis 1: commercial vs. military markets. *Commercial markets can be expected to lead or equal military markets in the introduction of technologically advanced products.*

Hypotheses 1 can be supported to a greater or lesser extent in every category of components in this study. In the general purpose microprocessor market, the military has, for the most part, been behind the commercial market in the development and implementation of these devices. Except for the DoD-defined 1750A architecture which was developed specifically for the military, military processors introduced during the 1980s have been based on commercial CISC processors created by commercial firms for commercial markets, especially the Intel 80X86 and the Motorola 680X0 families. The introduction of military processors has generally lagged behind the commercial introductions by a year or more.

Although DARPA played a significant role in the development of RISC architectures, the military has been slow to adopt ICs based on these architectures, even though they promised manyfold improvements in processing speed. RISC microprocessors are now being adopted into military systems, but only after they have started to play a significant role in commercial markets.

There is evidence to support the hypothesis with respect to SRAMs, although the differences between technologies in commercial and military markets are small and not statistically significant. Commercial SRAMs lead along most characteristics most of the time. Support for the hypothesis is strongest in rad-hard SRAMs. These are significantly different from both commercial and non-rad-hard military SRAMs, much more expensive

than other military SRAMs, and are developed considerably later in comparable capacities.

Although the data indicate that military programmable ROMs lag their commercial counterparts somewhat, the results of regression analysis show that the difference between times of introduction of commercial and military ROMs in the market is not statistically significant. There is support for Hypothesis 1 in the programmable ROM market, but it is quite weak.

Finally, the analysis of DSPs is limited by the fact that only single-chip DSPs and multi-chip DSP systems were analyzed. Individual building blocks which are used for high-performance applications and which have historically been favored by the military are excluded from the study because they cannot be compared with other DSPs on an equal basis.

There is little evidence in support of Hypothesis 1 with respect to DSPs, even without the presence in the data base of high-performance building-block ICs which have been favored by the military. Military ICs lead in throughput, a performance characteristic which is probably more important to users than many other characteristics of DSPs. Although military DSPs are more expensive, in the few cases where both throughput and price are available, military ICs do not stand out from their commercial counterparts in price/performance ratio. For the most part there is not much difference between commercial and military parts, however, as corroborated by the integrative analysis. The late recognition of commercial applications of DSPs and the large number of such applications which have now been identified, make it likely that the technology lead enjoyed by military DSPs will not hold for long.

As can be seen from this summary, data generally support the hypothesis that commercial markets either lead or equal military markets in IC attributes. The degree of difference between the two markets differs, depending on the component in question. In some components, like microprocessors, the military is definitely behind the commercial market. In other components, like DSPs, programmable ROMs and non-rad-hard SRAMs, the differences are not large.

However, it should be noted that one of the major reasons for military support of semiconductor R&D is assuring that military components will lead their commercial counterparts in areas critical to national defense. This study shows that military components do not lead commercial components, and in cases of near-parity between commercial and military components, the differences are usually in favor of commercial components. This means that the military's efforts to regain the leadership position in

semiconductor manufacturing through R&D expenditures have not been successful during the 1980s. It also means that an R&D funding policy based on the assumption of leadership needs to be carefully re-thought.

One area which stands out as needing government attention is the area of rad-hard ICs. The fact that the difference between rad-hard and non-rad-hard SRAMs is statistically significant, combined with the fact that SRAMs are often used as manufacturing technology test devices, indicates the need for greater support for these technologies if requirements for rad-hard components exist. The biggest problem with assessing the need for additional funding for rad-hard research is the scarcity of testing of commercial components for radiation hardness. As commercial manufacturers move toward technologies with greater radiation tolerance (albeit for reasons unrelated to the military's needs), the testing of commercial components would indicate whether commercial components can be used to satisfy some military needs, and will provide greater support for funding needs in those areas which are not likely to emerge from commercial R&D.

> *Hypothesis 2: evolutionary development strategy vs. skipping product generations. The government's strategy of skipping product generations does not produce advanced ICs faster than commercial evolutionary development.*

Hypothesis 2 can be supported by the data in all four component groups. With the possible exception of DSPs, neither commercial nor military ICs appear to have taken leaps across generations, as one would expect if the generation-skipping strategy were effective. All IC characteristics examined in the study showed a gradual progress from one generation to the next in both commercial and military markets. There is no indication that the ICs available to the military are any different from those that would have resulted from gradual evolutionary development or adaptation of commercial components and technologies to military applications.

As for DSPs, the support for this hypothesis is less unequivocal. There is one possible exception to the finding that neither commercial nor military components skipped generations. If the TRW/Motorola CPUAX, developed under Phase 2 of the VHSIC Program, becomes quickly available for incorporation into weapons systems, it might be considered a generational advance. Since the IC has been released in the past few months, it is too early to determine whether it will remain a laboratory curiosity or

actually become a production component before commercial ICs of comparable complexity are available in the market.

> *Hypothesis 3: systems vs. component orientation. Funding military microelectronics R&D through systems-oriented firms delays the creation of most advanced components because systems firms do not have improvement of components as a priority.*

Support for Hypothesis 3 is mixed. There is support for it in the microprocessor data. Systems firms appear to be slightly behind components firms in introducing processors with similar characteristics (with the notable exception of Hewlett-Packard), but the difference is not statistically significant when multiple component characteristics are taken into account.

The digital signal processor data do not support the hypothesis. Both the individual component analysis and multivariate regression analysis show that DSPs produced by systems-oriented firms are introduced before DSPs of similar characteristics are introduced by component-oriented firms.

There is not sufficient data about systems-oriented firms to evaluate the hypothesis in the case of SRAMs. There is some indication that systems-oriented firms produce SRAMs which are more expensive than ICs produced by their component-oriented counterparts, but the majority of the points in the data base which correspond to systems-oriented firms are also military SRAMs, which are more expensive than commercial SRAMs.

Finally, Hypothesis 3 cannot be supported by the data for programmable ROMs. Component-oriented firms led ROMs produced by systems-oriented firms in every individual IC characteristic except for power dissipation, but the differences are not statistically significant in an integrative analysis. Although the result cannot be stated categorically due to comparative scarcity of data on ROMs produced by systems-oriented firms, the differences in the time of introduction of ROMs by systems- and component-oriented firms are small.

The implications for the R&D funding strategy with respect to the hypothesis are clear. With the exception of DSPs, systems firms appear to be on par with or slightly behind component-oriented firms. While the hypothesis in its strong form cannot be supported, neither can the contention that systems firms are likely to develop *more advanced* components because they are driven by systems considerations.

It is interesting to note that component-oriented firms lead in components where commercial markets have led military markets (i.e., microprocessors, SRAMs, and programmable ROMs). DSPs are different, perhaps in part because the major interest in these markets prior to 1980 was military. This has begun to change, however. As more DSP-intensive commercial applications have been envisioned, from graphics to medical image processing to sound processing to high-definition displays (commonly referred to as HDTV), the commercial interest in DSPs has risen. If history repeats itself, the commercial industry will take over the lead in this component group as well. In that case, it will be interesting to see whether systems-oriented firms can maintain their advantage, or whether other component-oriented firms join Texas Instruments in its dominance of the DSP market.

> *Hypothesis 4: technology leadership vs. cost followership. The government's preference for funding advanced product R&D precludes the government from taking advantage of low-cost circuits created by firms which choose the technology follower strategy.*

Microprocessors are different from other components in that a firm can choose to be a leader or follower either in architecture or in manufacturing technology. Consequently, these were treated separately in the analysis. With the exception of the 1750A architecture which was developed specifically for the military market, the government bought microprocessors based on architectures developed for commercial markets. It has dealt with both architecture leaders and followers. The prices of architecture follower ICs are not significantly different than those of architecture leaders, and the differences between architecture leaders and followers were not significant in multivariate analysis. Hypothesis 4 cannot be supported in this market, perhaps because the demand for microprocessors has been sufficient to keep prices high for architecture leaders and followers in both commercial and military markets.

There is not sufficient information in the database to test the hypothesis about the differences between firms using leader and follower strategies in microprocessor fabrication technology, in DSP, or in programmable ROM markets.

Information on technology followers is also scarce with respect to SRAMs. However, in cases where data are available, the hypothesis cannot be supported--although they introduce consistently less expensive SRAMs, followers are considerably behind the leaders by a length of time that may not be acceptable to the government.

CONCLUSIONS AND POLICY ISSUES

What do these results tell us about the success or failure of the military's semiconductor R&D funding strategy? Let me address several issues.

Choosing Technologies That Should Be Funded

Although it was a leader early in the history of the semiconductor industry, few areas of DoD leadership remain. Trends indicate that the leadership of commercial semiconductor manufacturers will continue. Given this and the relative sizes of military and commercial markets, it does not make sense for the military to spend money on advancing the general state of the art in the semiconductor industry. Now that the relative technological positions of commercial and military components have been reversed, this type of spending cannot be justified by potential "spin-offs" from military to commercial applications as it was early in the history of the industry. Rather, it is more sensible to address DoD funding to areas of special DoD interest, such as the development of radiation-tolerant components, and to focus on keeping up with commercial markets. It makes sense to institutionalize the process of "spin-on" from commercial to military applications--a process that is already taking place informally, as demonstrated by the choice of popular commercial RISC processors as military standards.

Sometimes the distinction between "military" and "commercial" technologies cannot be easily made, of course. Funding of research in gallium arsenide (GaAs) components is an example. Commercial industry exhibited great enthusiasm for GaAs early on, when it was found that ICs made of this compound are inherently faster and have lower power dissipation than their silicon counterparts. However, as manufacturing problems grew and the characteristics of silicon components improved, commercial industry's interest in GaAs waned. DARPA was one of the few parties still interested in the development of GaAs components and continued funding R&D. Commercial interest is now reviving with the realization that GaAs components may be the best way to implement some communications and high-definition display applications. If commercial volumes for GaAs ICs exceed military volumes at some future time, DARPA will have funded a "commercial" technology. The funding of GaAs research to date, however, has not been based on possible future commercial uses but on military advantages provided by the technology.

The view expressed here appears to be at odds with the views expressed by the advocates of DoD funding for "dual-use" technologies. "Dual-use" technologies are

defined as those that can be used by both commercial and military markets and would lead to a closer integration of commercial and military economies. The argument in favor of DoD funding for such technologies is that this would advance the state of the art of weapons systems, while simultaneously helping the U.S. semiconductor industry recapture its international primacy.

Actually, the conflict with this argument is less in whether the development of "dual-use" technologies should be subsidized by the government (there are well-developed economic arguments that justify the government's involvement in R&D funding which serves to improve the general state of knowledge), but in the role of the DoD as the agency that takes a leading role in such funding. The DoD's role could be justified while the DoD was the first and major beneficiary of advanced technology, while it stood as first and major buyer of ICs produced by the technological leaders in the industry. The DoD is no longer in this position. Furthermore, its resources are limited and will be further reduced as the country struggles to find relatively painless ways to deal with the budget deficit. Therefore, it appears more sensible to focus DoD's R&D resources on technologies which are important for national defense, including the translation of commercial advances into military uses, and address the issues of national competitiveness in a different manner.

This argument has direct bearing on the DoD's participation in the Sematech consortium. It is too early to judge whether Sematech is, indeed, the means by which the U.S. semiconductor industry will achieve worldwide semiconductor manufacturing leadership, the early stated goal of the consortium. According to the CBO evaluation, "Sematech's principal contribution so far has been in strengthening the lines of communication between producers and users of semiconductor manufacturing equipment."[1] This is a laudable achievement which is likely to have positive long-term consequences for the U.S. manufacturing base, including the defense manufacturing base. It is not clear, however, that the government's $100 million per year contribution (approximately 50 percent of the consortium's operating funds) should be channeled through the DoD, given the general nature of the consortium's goals.

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[1]The Congress of the United States, Congressional Budget Office, *Using R&D Consortia for Commercial Innovation: Sematech, X-Ray Lithography, and High-Resolution Systems*, July 1990, p. xi.

Parts of the Industry That Should Be Funded

R&D funding should be directed toward firms that are most likely to have a production capability in the component of interest. For some components this might mean going to systems firms, but the general assumption that systems considerations will result in advanced components does not hold in either military or commercial markets.

When observers focus on the high cost of military systems, they often note that the firms which participate in the military market either do not participate in the commercial market, or do so with divisions which are separate from their military divisions. There are many reasons for this, ranging from accounting requirements on government contracts to testing and traceability requirements on components sold to the military. Given the very high and increasing cost of building and maintaining semiconductor manufacturing facilities, and given the increasing microelectronics content of weapons systems, it is not surprising that costs of weapons systems grow as long as firms which produce military ICs are not in the business of mass-producing ICs. Although military systems contractors may be willing to invest in such facilities as long as the government is willing to subsidize the investment, the components they produce are likely to be very expensive because of the small number of units over which the cost can be amortized. Furthermore, firms which produce small numbers of ICs are not in a position to take advantage of the large economies of scale characteristic of the commercial industry. If the costs of weapons systems are to be contained, the electronics must be produced by firms which have incentives and opportunities to reduce the cost of ICs.

Use of Commercial Components in Military Systems

Greater use of commercial components in military applications has been urged in previous studies. This study took a different approach, but ended up with conclusions that support the earlier work. In most instances, commercial components lead their military counterparts, whether or not such leads are statistically significant. Reliability,[2] temperature tolerance, and radiation tolerance of commercial components have increased over time, and have often been "tested" by the marketplace. In cases where there is a delay in the introduction of military components, it is often caused by additional military requirements for packaging and testing which must be met to translate commercial

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[2] *Report of the Defense Science Board On Use of Commercial Components in Military Equipment*, June 1989, pp. A19-A20.

components into military ones. If these requirements can be relaxed, the DoD would be able to take greater advantage of the current state of the art.

And Finally...

Perhaps the trouble is not with R&D at all. According to E.D. Maynard, the director of the DoD VHSIC Program in 1986,

> one major reason for this erosion of capability [in U.S. weapons systems] was that it was taking longer and longer for the DoD to move high performance ICs from the development laboratory into military systems. Commercial use of a given level of IC technology, by contrast, often preceded military applications by as much as 8 to 10 years.[3]

This study indicates that the problem with weapons systems capability, if it exists, does not stem from the availability of useable military components with performance characteristics close to those of their commercial counterparts. Many of the military ICs examined in this study are quite close in capability to commercial ones--certainly, nothing like 8 to 10 years behind. If there is a problem of moving these components into systems, R&D focused on advancing the state of the manufacturing technology will not help solve it. A formal study of the time period and process for moving commercial and military ICs from the laboratory into systems would locate and address impediments to rapid component integration. Such a study is the next logical step in the research.

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[3]E.D. Maynard, *VHSIC Annual Report for 1986*, p. 10.

Appendix A
MICROELECTRONICS TECHNOLOGY[1]

This appendix provides a brief tutorial on technical terms used throughout the text. It is designed so that someone without technical knowledge of electronics can understand how microelectronic circuits work, how they are produced, and how they are classified. The information presented here is by no means complete, but should make the technical concepts more accessible.

SEMICONDUCTOR SCIENCE

A semiconductor is a material which normally does not conduct electric current, but can be made to do so. Semiconductors have electrical properties which are intermediate between conductors and insulators. Metals, which are conductors, have many electrons free to move through the material. In the presence of an electric field, these electrons move, resulting in a current. Glass, rubber and most plastics, which are insulators, do not have free electrons, so conduct no current. Semiconductors have a few free electrons, but not enough to conduct electricity when they are very pure.

In order to make silicon or another semiconductor useful for microelectronic devices, specific kinds of impurities are introduced into very pure material in a controlled manner, a process called doping. The impurity atoms take the place of silicon atoms in the crystal lattice and provide the current-carrying capacity. Two types of dopant atoms can be introduced. When atoms which have one more electron than silicon are introduced, n-type silicon is created. The designation signifies the presence of excess negative charge carriers. When atoms which have one less electron than silicon are introduced, p-type silicon is created. "P" denotes a surplus of places for electrons, (referred to as holes) and signifies the presence of excess positive charge. Semiconductor devices rely on the properties of adjacent regions n-type and p-type silicon.

IC PRODUCTION PROCESS

The IC production process begins with circuit design, which, in turn, starts with the determination of circuit function and the creation of logic diagrams. After basic

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[1]Although the information presented here is an amalgamation of several sources, the basic organization is similar to that of Appendix A, "Current Microelectronics Technology," Office of Technology Assessment, op. cit., pp. 28, ff.

function definition and component layout, detailed designs are made. Computer-aided design (CAD) systems that help the designers fit the components into the available space are absolutely essential for the mask-design phase, where transistors and interconnections are laid out. Some of the more complex circuits are combinations of standard subcircuits. Other computer tools are used for checking designs against logic equations, for modeling circuits, and for simulation. The designs produced in this phase are fabricated into various masks. Mask fabrication, requiring several specialized optical machines, is usually carried out in a specialized mask-making center.

The basic (and highly simplified) process for producing an IC is shown in Figures A-1 and A-2. Figure A-1[2] shows the steps in wafer processing. Wafer fabrication is a laborious process, although the use of computer-controlled processing and tracking is increasing. Special projectors are used in which the alignment of successive mask patterns is a major concern. Cleaning and manipulating the wafers must be performed with great care. The manufacturing takes place in "wafer fabs" of an IC house. It is here that the companies make their major capital investment in equipment and ultraclean rooms.[3]

Very pure crystalline silicon, in which a controlled amount of n-type impurities is added during growth, is produced in rods 6 or more inches in diameter. The rod is sawed into thin wafers which are polished and used in IC production. Each wafer accommodates several hundred identical ICs which are separated after fabrication. Cassettes, containing several wafers on which the same circuit design is fabricated, are usually processed in a batch. First, a thin layer of highly regular silicon is grown on the surface of the wafer and oxidized at a high temperature, producing a layer of insulating oxide (silicon dioxide, SiO_2). The surface is then covered by a photosensitive material, called resist. A glass mask on which the pattern of the design has been etched, is placed

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[2]Similar information is available from a variety of sources. This figure is from Hazewindus, op. cit., p. 52.

[3]Class 10 clean rooms in which today's ICs are fabricated are built to very stringent specifications: no more than 10 0.5-micron particles per cubic foot of air (a human being, breathing while standing still, generates 500 particles per minute), floors isolated from the surrounding building with vibration-damping seals (tolerances are so tight that a passing truck or someone running through the building can throw mask-projection equipment out of alignment), and buildings located only in places with stable soil. The next generation of ICs may require sufficiently high cleanliness standards that humans will be precluded from being in the cleanrooms at all. [Otis Port et al., "Intel: The Next Revolution," *Business Week*, September 26, 1988, p. 77.] Intel's new Albuquerque plant, where the 80486 is produced, has a Class 1 rating: less than one 0.2-micron particles per cubic foot. [O. Port, "Superchip Plants: Where 'Clean' Has a Whole New Meaning," *Business Week*, September 1988, p. 77.]

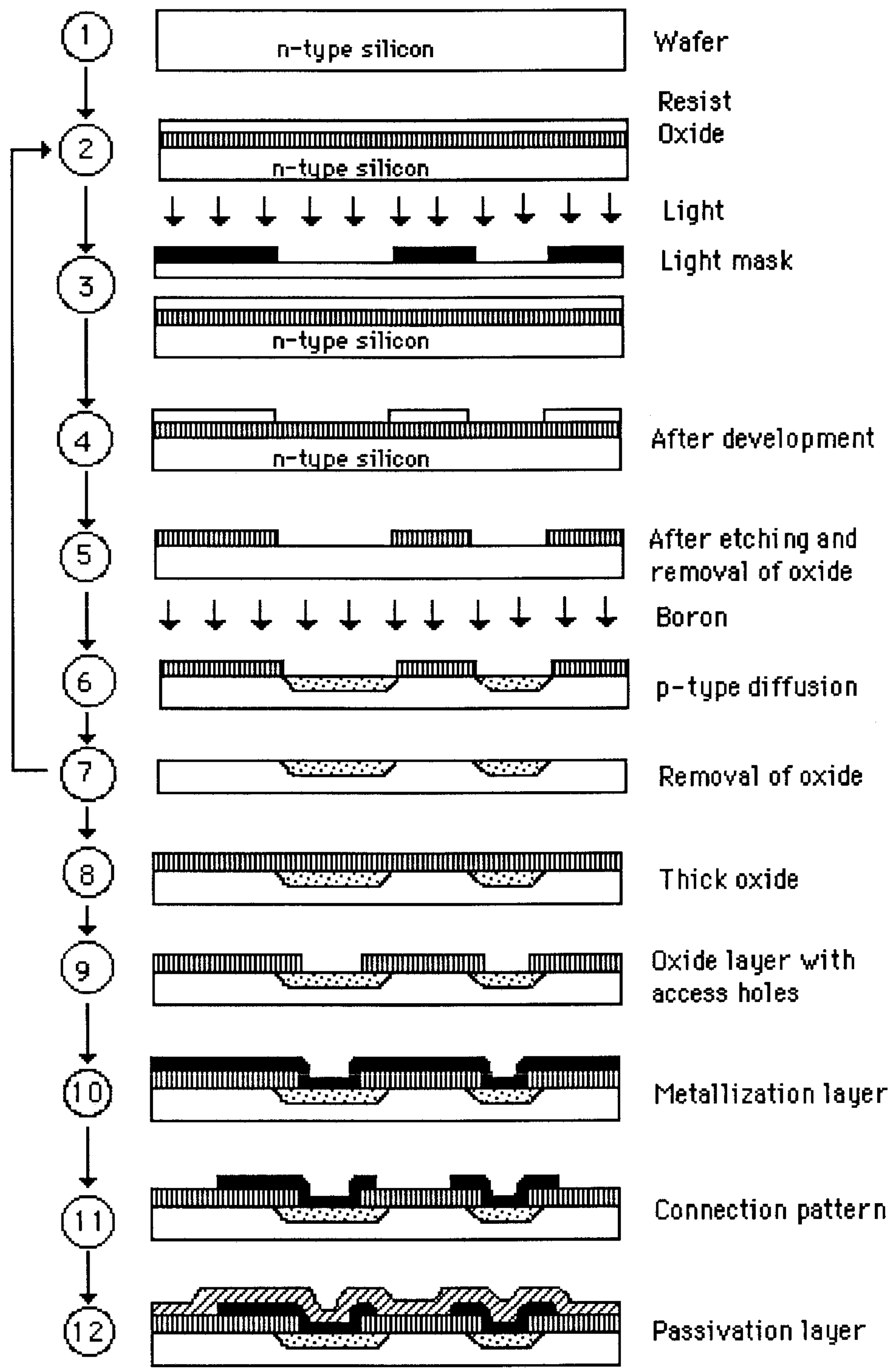

Fig. A-1--Basic wafer processing

on top of the wafer and irradiated with a light source. The exposed resist is then developed and removed. The oxide which remains in places not covered by the resist is then removed by an etching process. Finally, all remaining resist is removed.

The wafer, which now contains exposed areas of silicon, is placed in a furnace in a boron or phosphorus atmosphere. The atoms from the atmosphere diffuse into the silicon crystal lattice at high temperature, producing regions doped with p-type impurities. Concentration profile of the dopant can be carefully controlled during the process through atmospheric dopant concentration and temperature. The remaining oxide is then removed, and the process is repeated to create other regions. Usually, a number of repetitions is needed to complete all necessary diffusions.

After all the diffusions have been completed, a thick layer of oxide is evaporated over the entire surface. Holes are made in the oxide and a thin metal layer is evaporated on the wafer. After a desired pattern of conductors is made using lithographic techniques, undesired metal is etched away, and a protective passivating layer is applied to the entire surface.

What happens to the wafer after it is processed is shown in Figure A-2.[4] After the wafer undergoes all the fabrication steps, it is tested to determine which of the circuits operate properly, a process often referred to as wafer probe test. The circuits which do not work properly are marked, the wafer is cut into individual dice, and marked dice are thrown away. Each good die is glued to a metal frame that contains the pins of the IC package, and the circuit is connected to the pins with very thin gold wires. A plastic or ceramic housing is provided around the IC, and the whole thing undergoes a final test before shipment.

This part of the manufacturing process requires a great deal of manual work. For this reason, many merchant IC manufacturers have established assembly facilities in low-wage-rate countries. Captive manufacturers in the United States and Japanese manufacturers have opted for automation instead. Packaging is very important in IC production because the package protects the circuit and allows it to withstand physical and some forms of radiation damage. In addition, ICs which are sold to multiple users must have packaging which allows ICs to be interchangeable.

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[4]Adapted from W.G. Oldham, "The Fabrication of Microelectronic Circuits," *Scientific American*, Vol. 237, No. 3, September 1977, p. 112.

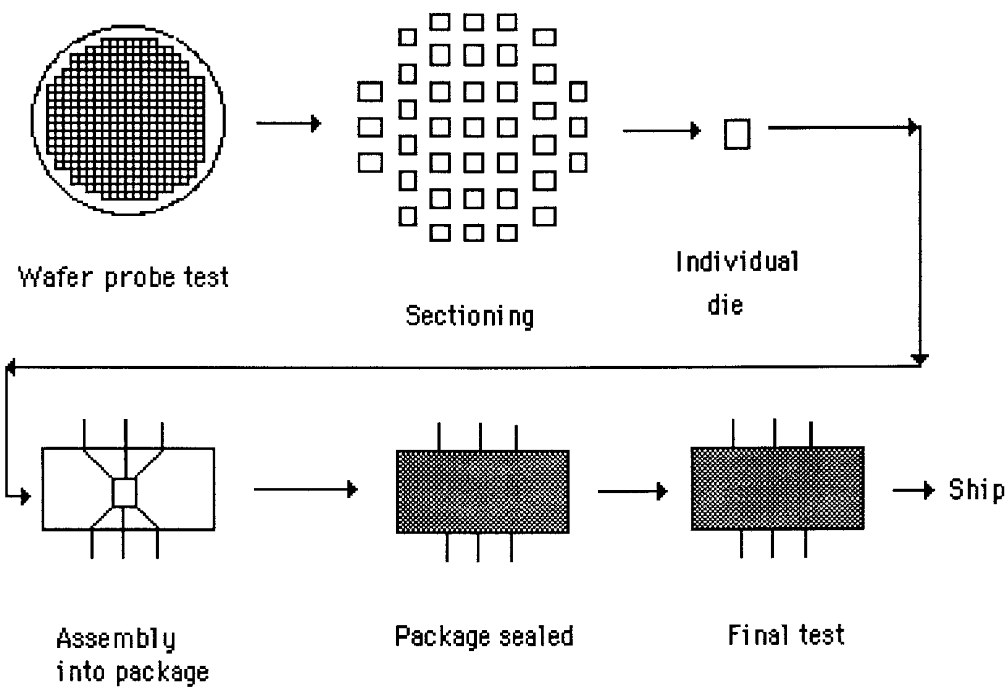

Fig. A-2--IC test and packaging

A good measure of quality in the manufacturing process is the yield (percentage of good circuits at wafer probe). Yield figures are closely guarded because they directly reveal profitability of a certain operation. New advanced circuits usually have yields below 10 percent; after some time, yields for standard products can be as high as 90 percent.

Over the years, industry has achieved tremendous advances in technology. The number of components per integrated circuit has doubled every year in the last twenty years. (The prediction that this would happen was made by Gordon E. Moore of Intel in 1964, and is known as Moore's Law. It has held amazingly true over the years and the broad range of technologies.) Whether this will continue to remain true is not clear. The major drivers in decreased size of ICs have been decreased size of individual cells, enlarged chip sizes and decreased line widths for conductors. Advances in silicon production technology have increased the standard diameter of wafers from 2 inches several years ago to about 6 inches today, which allows production of nine times as many

chips from the same set of processing steps, and allows cost to fall. Some manufacturers are now using 8-inch wafers to further increase productivity.

One of the most significant economic features of IC production is the learning curve. Figure A-3 illustrates price per bit versus volume of production for a particular type of random-access memory (RAM) chip.[5] The price per bit drops to 68 percent of original price every time the production volume is doubled. The basic reasons for such reductions are improvements in manufacturing methods, allowing higher yields per wafer, increased size of wafers, increased number of circuits per wafer, and the transfer of labor operations from high-wage to low-wage countries or to automation.

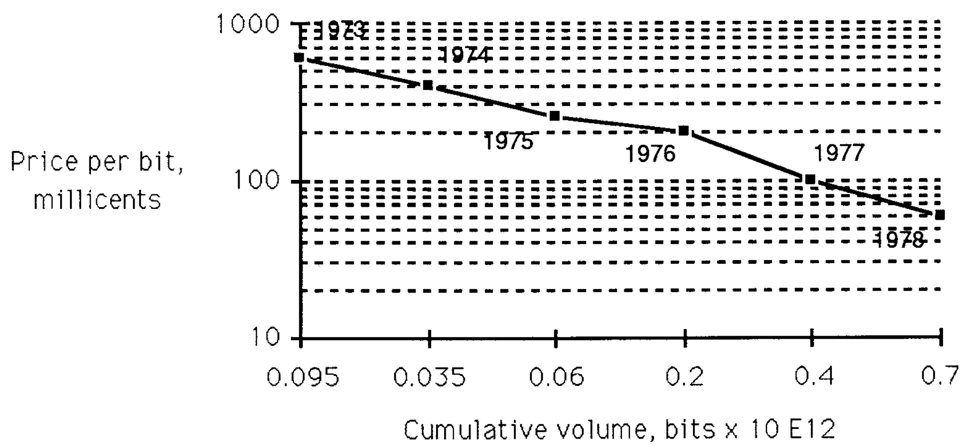

Fig. A-3--Price per bit, NMOS DRAM

Several manufacturing technology advances are critical for further advances in ICs. Computer-aided design (CAD) technology has to improve in order to make VLSI design practical and cost-effective: the large and growing number of individual components has created enormous computer time requirements for design and simulation. Progress has been made in the area of lithographic techniques; manufacturers have now approached the limit of miniaturization that can be produced with visible light. X-ray lithography is a promising technique that is being developed for the future. One of the most critical areas for improvement is circuit testing. Circuits have become so complex

[5]Hazewindus, op. cit., p. 13.

that it has become increasingly important to design testing programs at the design stage. This is not yet common practice, however. Fully automated CAD-CAM (computer-aided design/computer-aided manufacturing) leads toward greater automation of chip production. New packaging techniques have been developed for VLSI circuits, since standard packages do not have enough pins to take advantage of full capabilities of these circuits. Multi-chip packages are being explored as a way to decrease delays resulting from relatively large distances between ICs and further improving system performance.

INTEGRATED CIRCUIT CLASSIFICATION

Integrated circuits can be classified in four different ways: by function, by level of integration, i.e., the number of components contained on a single IC, by type of transistor used in circuit design, and by material from which the circuit is fabricated. Each of these is described below.

Classification By Function

One way to classify integrated circuits is by the function which they are designed to perform. This classification, shown in Figure 1 of Section II, is the basis of organization for the research presented in the main body of the paper. For the sake of completeness, this section includes some definitions found elsewhere in the paper.

Integrated circuits can be either digital (i.e., work with only 1s and 0s) or analog (i.e., work with any number within a range and transform an input signal into an output signal in accordance with a predictable functional relationship). Data processing equipment is based on digital circuits. Since the world is usually analog, a special group of integrated circuits converts analog signals to digital ones (A-to-D converters) and the other way around (D-to-A converters) to permit interaction between analog sensors and data processing equipment.

Within the group of digital ICs, there are four major types of circuits: memories which store data; microprocessors which process and sometimes store; logic circuits which perform mathematical functions; and application-specific circuits which combine different functions in ways designed by the user.

Memories are designed to store information. Their capacity is measured in the number of bits (individual 1s and 0s) that they can store. There are three types of digital memories: dynamic random-access memory (DRAM), static random-access memory (SRAM) and read-only memory (ROM). All of these memories allow any location to be accessed in the same amount of time, a capability known as "random access." These

three types of memory span the range of "volatility," i.e., they have different capabilities for maintaining the integrity of data as power is applied to the circuit.

DRAM stores data in very simple cells, composed mainly of capacitors. It is the most volatile of the three types of memory. Information is stored in the individual cell as a charge on a capacitor--a level above a certain threshold is interpreted as 1, the level below the threshold is interpreted as 0. All capacitors allow stored charge to leak away with time, but microelectronic capacitors are so small and contain such small charges, that unless they are "refreshed" or recharged every few milliseconds, an error may result when the signal level dips below the threshold.

SRAM is designed with more complex memory cells which are constructed so that the signal remains unchanged as long as power is on. A specific signal must be sent to change the state of a transistor used as a means of designating 1 or 0 in SRAM.

ROM is non-volatile, i.e., it preserves data even after power is turned off. As the name implies, read-only memories permit the user to conduct only read operations, and are programmable only once, by the manufacturer. In order to increase usefulness and versatility of ROMs, manufacturers produce programmable ROMs, or PROMs, which can also be programmed only once, but by the user. Several types of re-programmable ROMs have also been introduced. Erasable PROM (EPROM) is generally erasable by irradiation with ultraviolet light. The chip has to be removed from the system for reprogramming, and all information is removed when a chip is irradiated. EEPROMs are electrically erasable, generally one bit at a time, but the chip can be left in place while the reprogramming takes place. This eases the process and creates flexibility comparable to that of DRAMs, with the addition of non-volatility.

Microprocessors are devices which perform a variety of arithmetic and logic tasks, specified by software, on data which are generally stored separately. The main use of these devices is as central processing units in computers. Digital signal processors are derived from general-purpose microprocessors by stripping away many of the functions and leaving processors capable of performing very fast arithmetic and logic operations. As microprocessors have become increasingly specialized, they have also spread into embedded control applications in everything from automobile engines to industrial machines.

The number of bits processed by a microprocessor at one time determines the precision of the computation--the more bits, the greater the precision. Processors communicate with other ICs via buslines, collections of "lines" which allow groups of data or program bits to be simultaneously moved between the processor and another IC.

Bus bandwidth is an important criterion of performance because it determines throughput of data and instructions. The greater the bus bandwidth, the faster the IC is able to operate.

Classification by Level of Integration

Another way to classify integrated circuits is according to the level of integration, i.e., the number of components on a single chip. Table A.1 shows the way integration level has increased over time.[6] As the design rule (i.e., the feature size which can be successfully fabricated) has decreased, more and more components have been integrated on a single chip. This has allowed both the reduction in cost per function and the increase in circuit speed to take place over the same period. Cost per function fell because of economies of scale: the cost of producing, testing, and packaging a circuit does not increase proportionally to the complexity of the circuit. Speed is increased because the gates are smaller and can be traversed by electrons more quickly.

Table A.1

LEVELS OF INTEGRATION

Level of Integration	Design rule (μm)	Number of transistors	Years (approx.)
Small-scale integration (SSI)	30-20	2 to 64	1960-1965
Medium-scale integration (MSI)	20-10	64 to 2,000	1965-1970
Large-scale integration (LSI)	10-3.5	2,000 to 64,000	1970-1978
Very large-scale integration (VLSI)	3.5-0.8	64,000 to 2 million	1978 to present
Ultra large-scale integration	<0.8	>2 million	1990 and beyond

SOURCE: Adapted from OTA, *Microelectronics Research and Development*, p. 29.

Classification by Type of Transistor

A third way to classify ICs is by the type of transistors used in their design. Many of the differences within any specific product group, such as speed and power consumption, arise from the difference in the type of transistor used for the design of a specific product. There are two basic types of transistors: bipolar and metal-oxide-

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[6]Unfortunately, there is little general agreement on what constitutes the boundaries of each integration category. The boundaries presented in the table are taken from the OTA document indicated as the source.

silicon field effect transistors (MOSFETs). These are further subdivided to describe specific structures of devices.

The simplest semiconducting device, a diode, consists of adjoining regions of n-type and p-type silicon, and conducts current in one direction, offering high resistance in the opposite direction. Two diodes, joined back to back within a single crystal of silicon, form a bipolar transistor. An npn transistor is composed of a region of p-type silicon sandwiched between two regions of n-type silicon; a pnp transistor is the reverse.

The FET is also composed of two islands of n-type silicon in a p-type substrate (or vice versa), but only the two doped regions have electrical connections. The middle region is used as a place where an electric field is set up to influence the behavior of the two doped regions. This type of transistor is called metal-oxide-semiconductor transistor because it uses metal for interconnections and oxide, usually silicon dioxide, as an insulator.

The most common bipolar circuits are ECL (emitter-coupled logic) and TTL (transistor-transistor logic). The most common types of MOSFETs are NMOS (n-channel metal-oxide semiconductor) and CMOS (complementary MOS). The differences between bipolar and MOS technologies are: speed (bipolar transistors are faster); power (MOS requires less power); and ease of fabrication (MOS has higher yields). Among the MOS devices, the lowest levels of power consumption can be achieved by complementary MOS (CMOS) devices which use both n-type and p-type FETs. The emerging semiconductor technology of the 1990s is biCMOS, a way of combining bipolar and CMOS transistors in a single IC.

CMOS circuits are made on the surface of silicon wafers. For this reason, this is known as "bulk CMOS." However, there are speed-power and radiation hardness advantages to fabricating circuits in a thin layer of silicon grown on a substrate of an insulator, such as sapphire. Circuits using these technologies, known as CMOS-SOS (silicon-on-sapphire) or CMOS-SOI (silicon-on-insulator), are still used in military and space applications, but they are expensive and difficult to manufacture. Improvements in bulk CMOS have extinguished the interest in SOI for most commercial semiconductor manufacturers.

Several different logic designs within the broad categories of bipolar and MOSFET transistors are shown in Figure A-4, although they are not described here.

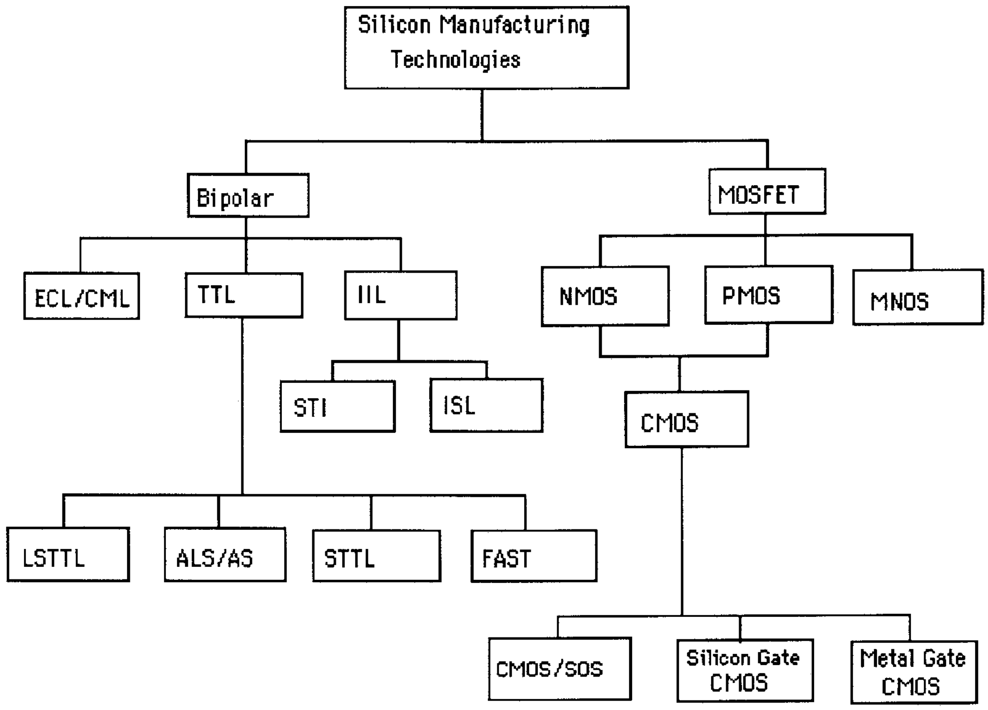

Fig. A-4--Silicon manufacturing technologies

Classification by Material

Finally, integrated circuits can be made of different semiconducting materials. This study addresses only those made of silicon, a material of which almost all circuits on the market today are made. Silicon is inexpensive and relatively easy to work with, which has made it virtually unchallenged as the material of choice for semiconducting devices since the first silicon transistor was fabricated in 1954. The vast majority of ICs are manufactured entirely of silicon and silicon oxides, except for metal interconnections which carry current to and from the circuit. Some circuits have been made of a combination of silicon and other materials in order to achieve greater radiation tolerance for military and space applications. Silicon-on-insulator (e.g., silicon-on-sapphire) circuits are made within a layer of silicon grown on a substrate of an insulating material. Continual improvements in the performance of silicon circuits, and massive investments in silicon fabrication technology, make the replacement of silicon by another material on

a mass scale unlikely in the near future. This does not mean, however, that alternatives to silicon are not being sought, especially for specific applications.

The most famous of the potential silicon replacements is gallium arsenide (GaAs). Because of the material's physical properties, GaAs transistors can operate up to five times faster than their silicon counterparts, and consume less power in the process. This makes them attractive for a number of applications, including supercomputers which require large numbers of fast ICs packed closely together.[7] GaAs ICs are also less likely to malfunction in the presence of radiation, which makes them attractive for military and space applications requiring rad-hard circuits. As attractive as its physical properties are, however, GaAs is a compound material which makes it more difficult to handle and to use for fabrication of reliable devices.

A number of other compounds is used to fabricate devices outside the integrated circuits category, but those will not be addressed here.

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[7]The desire for speed in such applications is obvious. Reduced power consumption simplified the removal of heat, generated as the circuit operates.

Appendix B
HISTORY OF MICROPROCESSOR DEVELOPMENT

DEFINITIONS

A microprocessor is a microelectronic device which can perform a variety of arithmetic and logic tasks specified by software.[1] Microprocessors generally perform the following functions:

- read and decode coded programs
- read data and programs stored in memory
- perform operations on data
- store data for later processing
- communicate with the outside world.

Although more and more of these functions have been incorporated onto a single chip as integration levels increased over time, microprocessors still need other ICs in order to operate. These peripheral chips may include

- the program, often in read-only-memory
- data, usually in random-access memory
- mathematics co-processors
- input-output interfaces
- a clock
- a power supply.

The primary reason for moving functions from peripheral chips onto a single chip is to increase microprocessor speed. Single-chip processors are faster because even small distances between external chips are much greater than the distances between different components of the processor, and data cannot be moved into and out of the processor as fast as the processor's internal clock dictates. A reduction in the number of external ICs also reduces the total cost and power consumption of the system in which the microprocessor is included, which allows systems to be lower-cost despite the incorporation of more expensive microprocessors.

A microprocessor communicates with associated ICs via buslines. In order to increase efficiency, separate buses for addresses, data transfer, and control instructions

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[1]Nico Hazewindus, *The U.S. Microelectronics Industry*, Pergamon Press, New York, 1982, p. 65.

are usually included. Bus bandwidth does not always correspond to the size of data blocks manipulated by the microprocessor internally, i.e., maximum size of internal architecture. Bus bandwidth and maximum word size of internal architecture have been used as a way to define successive generations of microprocessors, often in a way that makes it difficult to tell which data block size is being discussed.[2]

Microprocessors are used to perform a variety of functions. They were originally used almost exclusively as central processing units (CPUs) in microcomputers, and this continues to be their major use, but they have now taken over functions of control for computer peripherals (e.g., keyboards and laser printers), automobile engines, and various industrial machines.[3] By 1987, industrial, communication, military, and transportation embedded control applications accounted for just under 30 percent of the $347 million microprocessor market, and the percentage was expected to rise over time.[4] In military applications, microprocessors provide the "brains" of "smart" weapons, as well as processing capacity in navigation and fire control computers.

Two different approaches to microprocessor architecture are on the market. The time which a processor needs to execute a program can be described by the formula

$$\text{Program time} = I \times C \times T$$

where I is the number of instructions in a program, C is the average number of clock cycles per instruction, and T is the length of a clock cycle.[5] The older approach is called complex (or sometimes complete) instruction set computing (CISC). CISC microprocessors operate on two levels. One level offers programmers machine-level instructions, the second implements these instructions in microcode. This allows CISC programmers to use high-level programming languages and to hand-craft microprocessor instructions for greatest efficiency. In the above formula, CISC processors minimize program running time (i.e., maximize processor speed) by minimizing I. Unfortunately, the more complex the instruction, the longer it takes the microprocessor to decode,

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[2]"Product Focus: 32-bit Microprocessors and Support Devices," *Electronic Engineering*, October 1986, p. 117.

[3]Microprocessors are often referred to as microcontrollers in embedded control applications.

[4]Dataquest Inc., quoted in V. Rice, "Move Over, Intel-Motorola. Here Come the 'Others!'" *Electronic Business*, October 1, 1987, p. 60.

[5]This formula appears in various sources. The notation above is taken from C. Barney and T. Manuel, "RISC: Is It a Good Idea or Just Another Hype?" *Electronics*, May 5, 1986, p. 30.

process, and execute it. CISC microprocessors have become very fast over the years by integrating more and more functions on one chip and by taking advantage of the reduced size of transistors.

A very different approach to microprocessor architecture is reduced instruction set computing (RISC). This approach minimizes program execution time by including fewer instructions in hardware and using software to execute more complex instructions as combinations of simpler ones. The instruction count of RISC programs is usually about 20 percent higher than in CISC programs. RISC designers work to increase overall microprocessor performance by gaining speed in the execution of instructions faster than they lose it by executing more instructions,[6] with the major goal being the reduction of C to one or less clock cycles per instruction. In other words, RISC designers hope that a decrease in C is more than enough to counteract the increase in I. Silicon compilers, instead of programmers, are used to optimize program design.

Another difference between RISC and CISC is the extent to which the two architectures allow parallel decoding of instructions. CISC processors can access instructions in words of various lengths, but RISC microprocessors use fixed-length instructions, 32-bits long in current-generation microprocessors. Fixed-length instructions not only eliminate the need for an entire section of control logic, but allow RISC machines to further increase speed by decoding bits of instructions in parallel--something that cannot be done in CISC chips because the location of an end-of-instruction marker is not fixed.[7] This makes RISC processors simpler and is one reason why RISC architectures require fewer transistors to execute.

The difference between CISC and RISC approaches is reflected in approaches to performance measurement in the two kinds of microprocessors. Since a single CISC instruction may be equivalent to several RISC instructions, the most common performance measure, millions of instructions per second or mips, is misleading when used to compare RISC and CISC processors. In fact, even more complex measures may be inappropriate for comparing RISC and CISC processor performance unless the test programs reflect the actual application in which the processors will be used. This does not stop people from using the measures, however, because it is relatively easy to understand. Proponents of RISC architectures claim that RISC performance is superior to CISC performance at any level of technology.

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[6]No byline, "MIPS--RISC offers $10,000/MIP Performance," *Electronic Engineering*, September 1986, p. 12.

[7]R.D. Ross, *The Future of RISC*, Cypress Semiconductor, 1989, p. 6.

This appendix traces the history of development of microprocessors. A sketch of that history, depicting the increases in performance (as measured by millions instructions per second, mips) over time, is presented in Figure B-1. One feature unique to microprocessors should be kept in mind throughout this account: different microprocessors are designed to use different operating systems, and run different sets of software as a result.[8] Once a system is designed around a particular microprocessor, another microprocessor cannot be substituted. Since software is a major investment for the user, most makers of microprocessors have gone to great lengths to make later products compatible with earlier ones. For instance, every member of Intel's 80X86 family and Motorola's 68000 family can run software written for earlier family members. Firms make the effort to assure compatibility, even at the cost of sacrificing some efficiency in their microprocessors, in order to provide customers with ease of upgrading and to make switching to another firm's product more expensive.

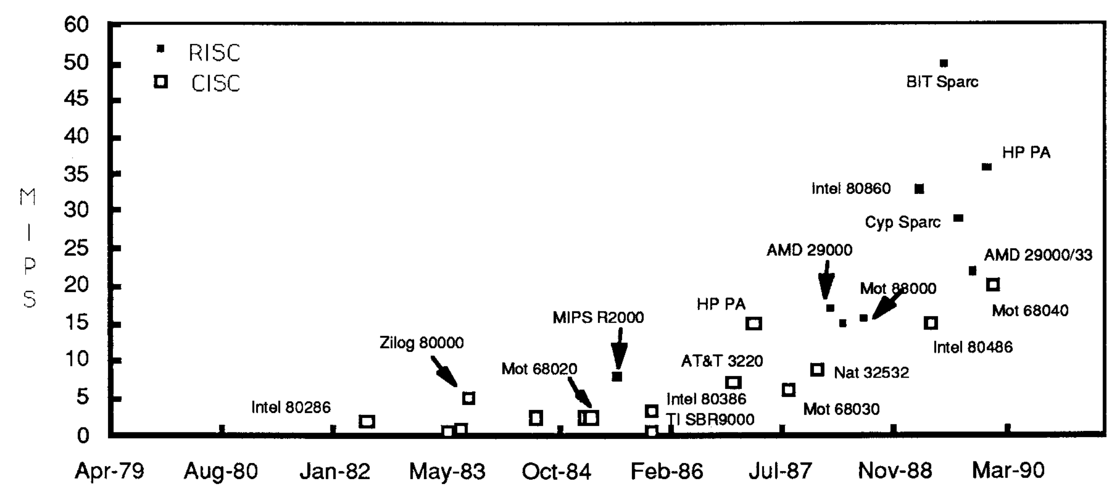

Fig. B-1--Microprocessor development, performance vs. time

The ability of microprocessor families to take advantage of large software bases has created market dynamics peculiar to microprocessors. Whereas computer makers can use memories and other chips manufactured by different suppliers, they are dependent on the microprocessor produced by a particular firm or that firm's licensees. In the early

[8]Systems based on the Motorola 68020 and 030 can run MS-DOS programs by means of simulation and translation software.

days of microprocessor development, designs proliferated, and extensive second-source agreements made their appearance. Manufacturers made these agreements not only to try to make their processor into a standard by proliferating it in the market, but also to allay fears that their demise would lead to the demise of their customers. Second sources provided assurances of a continuing and plentiful supply to large volume users, as well as assuring the existence of many and varied peripheral chips to increase the versatility and usefulness of the processor. Second-source agreements generally involve an exchange of microprocessor masks and designs for license fees, masks and designs of peripheral chips created to support the microprocessor, technology exchange, or purchase of significant numbers of components from the original source.[9]

With this in mind, let us now chart the timeline of microprocessor development.

CISC

The first microprocessor, the 4004, was introduced into the market by Intel in November 1971. The invention was spurred by a request from a Japanese calculator manufacturer, Busicom, for a chip set for a high-performance programmable calculator. Intel eventually returned Busicom's $60,000 design fee in order to recapture the rights to the chip.[10] The first true general-purpose microprocessor, the Intel 8080, appeared on the market in 1974.[11] This eight-bit microprocessor was developed at the same time as the earlier 4-bit chip.

16-bit Microprocessors

Texas Instruments pioneered the first 16-bit microprocessor in 1978.[12] Intel introduced its 16-bit design, the 8086, in 1978 as well, after an R&D process which took

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[9]For example, a second source agreement between Motorola and NCR for Motorola's 68000 processor included no up-front money but purchase by NCR of a substantial number of processors and peripheral chips from Motorola. [*Electronic News*, September 1, 1980, p. 1.] Motorola's agreement with Signetics/Philips included development of up to 30 peripheral circuits for the 68000 family. [*Electronic News*, March 9, 1981, p. 14.] Intel obtained CMOS manufacturing expertise from Harris in exchange for a license of the 8086. [*Fortune*, October 1983, p. 85.]

[10]*A Revolution In Progress... A History of Intel To Date*, Intel Corp., 1984, p. 12.

[11]The chips were sold at $360 each. David House, vice president and general manager of the Microcontroller Group, said that R&D costs were recovered in the first five months of shipment. Intel, op. cit., p. 14.

[12]No byline, "Shifting Fortunes," *The Economist*, April 25, 1981, p. 102.

approximately 5 years.[13] Motorola introduced its 16-bit processor, the 68000, in June 1979, about a year after Intel. The 68000, a follow-on to Motorola's 8-bit microprocessor, the 6800, was perceived as superior to the other chips on the market at the time. Intel's 16-bit chip was not catching on as well as expected, and Motorola started eroding Intel's market share. Motorola's strategy was to line up a strong team of second sources and to rely on them for much of the peripherals development.[14] Its list of second sources for the 68000 included Rockwell, Philips/Signetics, Hitachi, EFCIS (Thomson-CSF) and Mostek (which joined the Motorola team at the same time as it stopped acting as Intel's second source). Motorola ported the AT&T UNIX operating system to the 68000 in 1980, and has been working since that time to get UNIX accepted as the vehicle for industry standard software.[15] The other part of Motorola's strategy was the announcement that the 68000 is easily upgradable to 32 bit architecture.

Intel decided that the best response to Motorola's assault on the market was an 8-bit version of the 8086--the 8088, introduced in 1979 with an 8-bit bus and a 16-bit internal architecture. The most significant design win for the 8088 was its selection by IBM for use as the CPU for the IBM PC. As other microcomputer manufacturers started making PC clones, they had to use Intel microprocessor architecture in order to assure software compatibility with the PC. The IBM win propelled Intel to market leadership and helped the company achieve its goal of having the microprocessor architecture which was considered virtually the industry standard.

In addition to Intel and Motorola, several other firms were designing original 16-bit microprocessors. After a $27 million, 4-year development effort, National Semiconductor introduced the 16000.[16] Although the 16000 was one of the most advanced 16-bit processors with its 32-bit internal architecture, by the time it was introduced, the available market was considerably narrowed by Intel and Motorola. Texas Instruments, once a microprocessor leader, entered its 99000 family of microprocessors in the computer peripherals and microcontroller markets, not dominated by Intel and Motorola. Zilog's search for a domestic second source was fruitless,[17] which

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[13]Ibid. An Intel publication claims the chip was developed in two years, but I think that the difference comes from the fact that the 8086 is the second 16-bit microprocessor attempted by Intel. The first chip, the 432, was not a commercial success.

[14]S. Russel and S. Zipper, "Intel, Motorola Tighten Hold on General-Purpose MPUs," *Electronic News*, March 8, 1982, p. 1 ff.

[15]Motorola Inc., *Motorola's 68000 Family: The Roots of an Industry Revolution*, not dated.

[16]*Electronic News*, March 8, 1982, p. 1.

[17]Ibid.

essentially ended its chances of being a mainstream producer. Inability to compete with Intel and Motorola relegated Zilog to niche markets, although a Zilog vice-president stated that the processor's high performance made it a leading device in military and other high-performance markets. In fact, Zilog claimed that its chip had a ten-to-one lead in military applications.[18]

The next generation of Intel's 16-bit microprocessors, the 80186 and the 80286, heralded the integration into the CPU of functions which were previously performed with peripheral chips. The 80186, introduced in 1982, was the enhanced version of the 8086 which included on-board support functions such as a clock controller, timers, and counters. It also ran software about 25 percent faster than the 8086 at the same clock speed. The 80286 was an upgrade of the 8086 with on-chip memory management, designed to allow users to perform multitasking. The 80286 had so many problems with its multitasking features, though, that it was mostly used as a faster version of the 8086: the 80286 could run the same software about 2.5 times as fast at the same clock speed. True multitasking capability had to wait until the next generation of Intel chips.[19]

Intel extensively licensed its microprocessors up to and including the 80286. Its second sources for the 80286 included Siemens, NEC, Fujitsu, and Advanced Micro Devices. As it moved to development and manufacture of more advanced microprocessors, Intel stopped development of the 80286 after a version which ran at 12 MHz. However, firms which built the 80286 under license continued to improve the chip after Intel stopped. Advanced Micro Devices is still building a version which operates at 16 MHz and is planning to introduce a 25-MHz version. Harris already introduced a 25-MHz version which can run DOS software faster than the 80386.[20]

Harris claimed the introduction of the first radiation-hardened microprocessor--the 80C86RH based on the Intel 8086. Harris started work on a radiation-hardened version of the 8086 following a technology exchange agreement with Intel in 1981, and released the first rad-hard microprocessor, hard to 10^6 rads total dose, in 1984. Texas Instruments introduced a radiation-hardened version of its 16-bit 9000 microprocessor in 1985. The TI microprocessor was manufactured in 2-μm bipolar, optimized for radiation hardness rather than performance, rated to operate at 9 MHz and to perform 0.55 mips.[21] Although it was no longer a major player in the commercial general purpose microprocessor

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[18]Ibid.

[19]F. Hayes, "The Spirit of '86s," *Byte*, March 1990, pp. 265-266.

[20]Hayes, op. cit., p. 269.

[21]"Technology '86: Solid State," *IEEE Spectrum*, January 1986, p. 56.

market, Texas Instruments continued to play an important role in the market for military microprocessors. At the end of 1985, Texas Instruments introduced the 16-bit SBR9000, a bipolar IC optimized for radiation resistance.[22] TI has also used the chips it developed under Phase 1 of the VHSIC Program to put together a data processing module executing the DoD 1750A architecture.

While 32-bit processors have now come to dominate the commercial markets, the military markets for embedded control are still using mostly 16-bit chips. Intel's 80C186 has the largest volume in that market.[23] Since the 16-bit 1750A architecture is standard for many DoD applications, it continues to be produced by a large number of military contractors.

32-bit Microprocessors

In 1981 AT&T created the first 32-bit microprocessor, the 32000, manufactured in CMOS. The processor had 3.5 μm gate lengths and operated at 32 MHz, almost twice as fast as the highest clock rate of 18 MHz, current at that time.[24] CMOS was just coming into the mainstream of IC manufacturing technology, replacing NMOS by having attained the speed of NMOS while retaining low power dissipation. During the 1980s CMOS emerged as the dominant manufacturing technology as it became clear that higher integration levels would necessitate development of technology which could operate at reduced power levels.

32-bit microprocessors had significant performance advantages over earlier generations of chips. Several factors account for this: 32-bit microprocessors can access 8 to 32 bits at a time; clock speeds were increased from 8 or 10 to 16 or 20 MHz; memory management and cache memory were integrated into the CPU for instructions and data.[25]

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[22] J. Szot and J. Eatman, "Radiation Hardening Through 2-Micron I^2L Technology," *Defense Electronics*, November 1985, p. 59.

[23] *Aviation Week & Space Technology*, February 12, 1990, pp. 117-121. The 1750A architecture was established by the Air Force and adopted by the Army in order to stop proliferation of military microprocessor architectures and to allow future military microcomputers to use the same software. Many observers consider this architecture obsolete now.

[24] "Technology '82: Solid State," *IEEE Spectrum*, January 1982, p. 49.

[25] Memory cache is a small amount of memory which is used by the processor for storing instructions which the processor "thinks" will be used most frequently. Before going off-chip for the next instruction, the processor checks whether an instruction is in the cache. If the cache has a high "hit rate," i.e., if many instructions can be found in the cache rather than off-chip, the processor can operate faster by taking advantage of faster access and shorter distances. "Motorola have a 256byte instruction cache on-chip but handle floating-point operation and memory management via closely-linked coprocessors. Intel has integrated the MMU but has decided to wait until a larger cache can be integrated. Zilog's Z80,000 has both a 256byte data and instruction

32-bit microprocessors can also address much larger amounts of memory—4 gigabytes for 32-bit processors, as opposed to 16 megabytes for 16-bit processors and 64 kilobytes for 8-bit processors.

National Semiconductor introduced the first commercial 32-bit microprocessor, the 32032, in 1983. Motorola introduced its 32-bit microprocessor, the 68020, in the summer of 1984.[26] The 68020 was rated at 1.5-2.5 mips at 16.67 MHz,[27] and by the end of 1985, Motorola was shipping 20-MHz versions. Other 32-bit microprocessors include AT&T's 32100 introduced in late 1985 and National's 32332 in early 1986. The Intel 80386, with 32-bit address and data buses, was introduced in 1986. The correction of earlier problems that plagued the 80286 gave it full multitasking capabilities. It runs at speeds up to 33 MHz, although the version with a 16-bit bus (the 80386SX) is slower. The 80386 was rated at 3.64 mips at 16 MHz, and averaged over 14 applications and 31 million instructions.[28] In late 1987 Motorola introduced the 68030, its second generation 32-bit microprocessor, rated at 6 mips. The 68030 was the first processor on the market with built-in data and instruction caches, as well as on-chip memory management, essential for multitasking.

Both Intel's 80386 and Motorola's 68030 are follow-ons to the firms' earlier chips. Some other manufacturers have provided upgrade paths from their earlier processors as well. For example, Zilog's Z80000 is a follow-on to the Z8000. However, National Semiconductor, AT&T, and Fairchild created completely new designs which are more efficient, although they sacrifice software compatibility.

With the introduction of the 80386, Intel broke the earlier pattern and did not second-source the chip. (IBM reportedly has a license to make the chips for its own use.[29]) As desirable as they were in the early stages of microprocessor development, second source agreements were not without problems. Mostek left Intel's team and joined Motorola's, claiming that Intel was not releasing information sufficiently quickly. Although AMD had a license originally, the license was revoked and the matter went into

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cache and MMU on-chip." ["Product focus: 32-bit Microprocessors and Support Devices," *Electronic Engineering*, October 1986, p. 117.]

[26]Motorola claims that the 68020 was the first "true" 32-bit microprocessor because all its key processing elements are 32 bits wide. The NS32032 had a 24-bit program counter. [Motorola Inc., *Motorola's 68030 Second-Generation 32-bit Microprocessor*, p. 5.]

[27]*Electronic Engineering*, November 1985, pp. 64-67.

[28]*Byte*, 1986 Extra Edition, pp. 89-106.

[29]F. Hayes, op. cit., p. 269.

arbitration.[30] The dispute over whether AMD's second-source agreement includes second-sourcing the 80386 still continues.

The Motorola chip of the same generation, the 68030, is not second-sourced either. There were problems between Motorola and Hitachi and the second-source arrangement for the 68000 family was terminated. Motorola's 68030 is the subject of a court battle with Hitachi. Thomson had some problems with Motorola, as well. Motorola has been meticulous about the enforcement of "equal exchange" spirit in their second-source agreements, making it clear from the start that they would refuse or slow down information release to their second sources until they got the promised chips or technology in return.[31]

By the time the 80386 and the 68030 appeared on the market, all but niche users of general-purpose microprocessors were committed to Intel or Motorola products because of large investment in software made with earlier generations of chips. Having proven themselves as capable and reliable suppliers, Intel and Motorola no longer needed to share their profits with other firms. Besides, second sources always represented the possibility of price competition, as Motorola found out when Hitachi started lowering prices on 68000 microprocessors. Refusal to share technology spared Intel and Motorola from potential price wars.[32] The refusal to license advanced microprocessors has lead to some interesting developments. For example, since Intel is not second-sourcing the 80386, it is now trying to take back some of the customers which it lost to its second sources on the 80286 when these second sources introduced improved versions of the 286. Intel is using advertisement to encourage customers to buy PCs based on the 80386SX rather than the 80286-based machines which contain 80286s made by other firms. It's not clear, however, whether the ads are attracting 286 customers to Intel or just giving people an option of buying less expensive systems instead of systems based on the full-blown 80386.

As microprocessor development proceeded, so did the efforts to produce rad-hard parts for military and space applications. Sandia National Laboratory developed a rad-hard version of Intel's 8085 microprocessor, hardened to 10^7 rads in 1985, and it was expected that the radiation tolerance standard would rise to 10^7 rads total dose as a result of this technological development. At that time, Sandia was also working on the

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[30]Ibid.
[31]*Electronic News*, April 27, 1981, p. 1 and interviews.
[32]*Electronic News*, August 31, 1981, p. 47.

development of a 32-bit microprocessor compatible with National Semiconductor's 32032, to be ready in 1987.[33]

In the 1980s commercial firms were also exploring rad-hard technologies. Harris has always been active in research and manufacturing of rad-hard circuits. In 1980-1981, MacDonnell-Douglas (MDAC) was doing work on manufacturing the 1750A microprocessor in silicon-on-sapphire (SOS), but found that the technology was unprofitable, given the small demand for rad-hard processors. After signing a cross-licensing agreement with Marconi, a U.K. firm which is part of GEC, MDAC decided to abandon its SOS effort and buy its parts from Marconi. Since that time Marconi has been the world's leading supplier of SOS microprocessors. As a foreign firm, Marconi does not receive U.S. government research and development funding, although it did receive some funding from the U.K. government and the European Space Agency.[34]

In the mid-1980s microprocessors became more specialized and moved out of data processing into embedded control. In 1989, 60 percent of 16-bit microprocessors shipped were aimed at embedded applications.[35] In the microcontroller market software compatibility is not an issue, so Intel's and Motorola's advantages in the data processing market did not translate into automatic dominance of the microcontroller market. Texas Instruments realized this when it became clear that TI was locked out of the general-purpose microprocessor market, and created a strategy focused on application-specific microprocessors.[36] TI's focus on the embedded control market was taking advantage of the fact that one way to increase the speed of CPUs is to off-load some of their tasks to peripheral processors, and that such processors constitute a high-volume business because PCs and workstations have separate processors to drive displays, keyboards, and other computer peripherals. TI also started aggressively pursuing microprocessor slots for digital signal processing,[37] which was explored in the section on DSPs. Several firms producing specialized products, such as Advanced Micro Devices, Harris Corp., National Semiconductor Corp., and Cypress Semiconductor gained market share by supplying the embedded control market. Many of these firms introduced high-performance chips aimed specifically at this market.

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[33]"Technology '86: Solid State," *IEEE Spectrum*, January 1986, p. 56.

[34]Firm interviews.

[35]Steve Goldstein of Ross Technology Inc., quoted in J. McLeod, "The Stakes Are Getting Higher in Embedded Control," *Electronics*, October 1989, p. 29.

[36]An application-specific device is more specialized than a general-purpose one, but is not user-specific.

[37]V. Rice, op. cit., p. 61.

The year 1989 saw the introduction of the most advanced generation of CISC microprocessors: Intel's 80486 and Motorola's 68040. Intel unveiled its chip in April 1989. The 80486 consists of an enhanced 80386 processor, an enhanced 80387 coprocessor, an integral cache controller, and 8K byte SRAM cache in one 1.2-million-transistor IC. Motorola's chip was formally introduced in January 1990, although information about it was available earlier. It, too, contains over a million transistors. Aside from using different operating systems, the general features of the chips are similar. Both processors include cache, memory management, pipelining, and burst-mode bus. Because these processors include so many transistors, some of the transistors are used for hardwiring the more commonly used instructions instead of executing them in microcode, a technique borrowed from RISC processor design and allowing much faster execution. Both the 80486 and 68040 execute in under two clock cycles instructions which used to take four to six cycles for earlier generations of chips.[38]

As microprocessors have become more complex and more sophisticated, they have also become much more expensive to develop. While Intel's 80386 cost $100 million in development costs, the 80486 cost $250 million.[39] And this does not account for investment for manufacturing equipment which has to be purchased before the chips can be produced.

RISC

Reduced instruction set computing originated in 1974 at IBM's Thomas J. Watson Research Center in a project to design a large telephone-switching network, with requirements for a capability to process 12 million instructions per second.[40] The study found that 80 percent of the computation for a typical program required only 20 percent of the instructions in the microprocessor instruction set. These 20 percent included basic operations, like addition and subtraction. The researchers also found that 80 percent of the engineering time on microprocessor design was dedicated to implementing 20 percent of the program--the most complex and least used 20 percent. When they redesigned the processor to take advantage of their findings, the improvement in performance was staggering. The new processor prototype ran at 10 mips at a time when the average processor speed did not achieve even one million instructions per second. It is not

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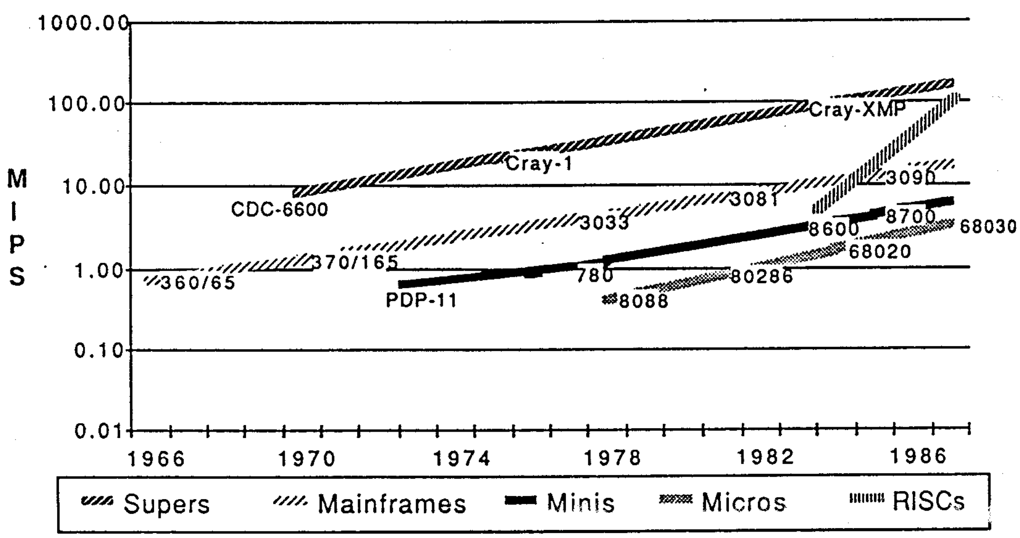
[38]J. McLeod, "Tough Choices Ahead," *Electronics*, May 1989, p. 71.

[39]C. Gottlieb, "Intel's Plan for Staying on Top," *Fortune*, March 27, 1989, p. 99. *Business Week*, September 26, 1988, puts the development cost for the 80486 at $300 million over 4 years.

[40]J. Cocke and V. Markstein, "The Evolution of RISC Technology at IBM," *IBM Journal of Research and Development*, Vol. 34, No. 1, January 1990, p. 4.

entirely clear why IBM did not proceed with the project at that time. The research on new microprocessor architectures continued throughout the country, however. Major research centers included Stanford University and University of California at Berkeley. Some of the university funding for advance architecture research was provided by the Defense Advanced Projects Research Agency (DARPA).[41]

Figure B-2 shows a comparison of performance growth rates in various types of computers. RISC demonstrates the steepest rate, bridging the gap between microcomputers and supercomputers. This is what makes it so attractive to users, especially makers of high-end workstations.



SOURCE: National Research Council, *Global Trends In Computer Technology and Their Impact On Export Control*, National Academy Press, Washington D.C., 1988, p. 50.

Fig. B-2--Computer performance growth

The first commercially available RISC processor, the Clipper, was introduced by Fairchild Semiconductor. This three-chip set grew out of supercomputer research done

[41]No byline, "Aerospace Firms Use Chips With 32-Bit RISC Architecture," *Aviation Week & Space Technology*, February 12, 1990, p. 120.

by Seymour Cray. It has more instructions than later RISC chips (101 vs. only 32 for Intel's 80860 or 51 for Motorola's 88000[42]), but it is definitely a RISC processor. When Fairchild was bought by National Semiconductor in 1987, the Clipper was sold to Intergraph Corp. because National already had a RISC offering of its own. Intergraph has the market lead both in commercial and military markets because it has been on the market the longest.

In 1983 development work was started on a chip that would eventually become SPARC.[43] Sun Microsystems introduced its first commercial realization of RISC technology, based on research conducted at UC Berkeley, in 1987.[44] The chip is available in a variety of implementations, which makes it popular. SPARC is a major contender for the role of industry standard for RISC because its instruction-set architecture is source-code compatible with the Sun workstations based on the Motorola 68000-family CISC microprocessors, and that makes it easy to quickly port the large number of applications available for Sun hardware.[45]

MIPS Computer Systems introduced its R2000 series of 32-bit RISC microprocessors in 1985, based on the design of John Hennessey, cofounder of the firm and Stanford professor.[46] These chips were rated at 3-10 mips, depending on the product selected.[47] The MIPS operating system is a combination of AT&T's System V.3 Unix and the Berkeley Unix, and has strong compiler support.[48]

Although it insisted for years that RISC chips are not suitable for personal computing, Intel finally entered the RISC market in 1989 with the i860, the first microprocessor to use 64-bit buses, which also combines a central processor, a graphics unit, and memory on one chip. Unlike other RISC chip sets on the market, the 1-million-plus-transistor 860 is the first one-chip RISC CPU. The chip's most remarkable feature is that under the right conditions it can perform three operations in a single clock cycle.[49] Although no application software was available for the chip at the time of release, Intel

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[42]*Electronics*, May 1989, pp. 70-76.

[43]No byline, "The RISC Business," *Electronics & Wireless World*, September 1989, p. 867.

[44]R. Brandt, D. A. Depke and J.W. Verity, "The Battle Royal In Chips," *Business Week*, November 27, 1989, p. 194. Although IBM put its early RISC chip into its PC RT, the computer was a commercial failure and was taken off the market.

[45]J. McLeod, May 1989, p. 76.

[46]J. Pitta, "Management by Parking Your Car," *Forbes*, August 21, 1989, p. 92.

[47]*Electronic Engineering*, September 1986, pp. 11-12.

[48]J. McLeod, May 1989, p. 76.

[49]The chip has three separate math units, and can perform integer math, floating-point addition, and floating-point multiplication at the same time. [*Byte*, May 1989, p. 114.]

was working with both IBM and Microsoft--IBM is working to design a board with the new chip for its PS/2, while Microsoft is working on the software. These are powerful allies in the race for market dominance. Intel is also pricing the 860 so that it will cost considerably less than the RISC solutions provided by anyone else in the market, while providing the integrated graphics capability that others do not offer.[50]

Every major semiconductor and computer firm has now acknowledged that RISC is an important part of the future of computing. Every major manufacturer of workstations has announced machines based on RISC processors, and RISC processor designs are proliferating. At present, there are five major RISC designs on the market: Intergraph's Clipper, Sun Microsystems' SPARC, MIPS Computer Systems' R3000, Intel's i860 and Motorola's 88000. Other designs are also available: IBM has its own RISC chip set, the America processor; Hewlett-Packard has HP PA (for Precision Architecture). Advanced Micro Devices is marketing its own RISC design, the Am29000, in the microcontroller market. Intel's i960 RISC microcontroller, based on the i860 but without the floating-point architecture features, is also aimed at the embedded control market.

The competition to establish a particular RISC microprocessor as industry standard is fierce. Sun Microsystems has been promoting its SPARC as an open architecture and a chip which is easily scalable, i.e., easily implemented in improved technologies. Sun has been licensing the SPARC architecture to different suppliers in hopes that the approach will encourage the proliferation of SPARC implementations and make SPARC industry standard. Sun's list of second sources includes Cypress Semiconductor, Texas Instruments, LSI Logic, Fujitsu Microelectronics, and Bipolar Integrated Technologies.[51] Until 1989, Sun was working with AT&T to develop a version of Unix which would work with SPARC and would give SPARC a great advantage over its rivals. Sun's agreement with TI calls not only for use of TI as a second source for Cypress Semiconductor's version of the SPARC chip, but for a design of a second-generation SPARC processor.[52] Although MIPS manufactured its own chips early in its history, it no longer does so, but uses a group of semiconductor manufacturers. These firms include Integrated Device Technology, LSI Logic, Performance Semiconductor, Siemens A.G. in

[50]Michael Slater, editor and publisher of *Microprocessor Report*, quoted in *Electronics*, March 1989, pp. 25-27.

[51]M. Alpert, "Why It's a RISC Worth Taking," *Fortune*, October 10, 1988, p. 112.

[52]R. March, "Pact with Texas Instruments Gives Sun a Needed SPARC," *PC Week*, September 5, 1988, p. 131.

Germany, and NEC in Japan. In order to promote its own RISC architecture, Motorola is championing an organization called 88Open Consortium Ltd. to foster interchangeability of software among all 88000 systems.[53]

The pattern of second-sourcing in the early stages of development is being repeated now with RISC chips. RISC chips are sufficiently new to the marketplace that none has yet established itself as "standard." It is, therefore, not surprising that there are more companies in the market than there are chip designs. MIPS and Sun Microsystems are ahead of the pack on "design wins" and second sources, but both Intel and Motorola have entered the contest. Although they have lost the advantage of software compatibility that made their CISC chips so important, Intel and Motorola may have a weapon against RISC manufacturers if their markets are threatened. Given their huge volumes, they may be able to cut prices of CISC chips to give them advantage over RISC chips in terms of price/performance ratios. They have not done this yet, but RISC offers sufficient performance improvements over CISC that this tactic may have to be used at some time. That's when the real determination will be made whether CISC can successfully compete with RISC.

The great attraction of RISC microprocessors compared to CISC is the significant improvement in the price/performance ratio which they deliver. The claims are not easy to untangle since different processors include different on-chip components and require different peripheral chips in order to operate.

Firms which entered the microprocessor market with the introduction of RISC architectures are leading the switch to new IC fabrication technology. Just as manufacturing technology moved from NMOS to CMOS in the early 1980s, it is moving from CMOS to bipolar or biCMOS in the 1990s. BiCMOS is attractive because it offers greater speed than CMOS, while maintaining low power dissipation. Bipolar Integrated Technology Inc. is working on a bipolar version of SPARC, while Cypress Semiconductor is working on a biCMOS implementation of the same architecture. Motorola and Data General are working on a bipolar version of the Motorola 88000, aiming at throughput of more than 100 mips.[54]

Although the DoD was slow to accept RISC, this has changed. The MIPS 32-bit RISC architecture is one of two standards chosen by the Defense Department's Joint

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[53]*Electronics*, October 1989, p. 51.
[54]*Electronics*, June 1989, pp. 110-113.

Integrated Avionics Working Group (JIAWG) for use in advanced aircraft computers.[55] The choice was made, at least in part, because of the chip's popularity in the commercial market. The other architecture chosen is the Intel 80960 RISC microcontroller. Apparently, two standards were chosen because contractors were already developing systems using more than one type of microprocessor.[56] It is interesting to note, however, that Motorola second-sourced its 88000 processor to Thomson-CSF for military and space markets, and Thomson announced that it will standardize its military products on that microprocessor. In the list of Top 100 defense electronics firms compiled by *Defense Electronics* magazine in January 1990, Thomson-CSF was ranked fourth on the basis of defense electronics sales, which makes it likely that the 88000 will become a significant player in military markets even though it has not been chosen as a standard. It also means that an attempt to create a standard for military markets may have come too early in the development of the market to determine which architectures will survive the likely market shake-out.

Virtually every supplier has its military RISC processor. For example, Hughes Aircraft's Intel-80960-based processor won the competition against Texas Instruments VHSIC computer for the avionics on the Lockheed Advanced Tactical Fighter (ATF) prototype. The other prototype in the (ATF) competition, manufactured by Northrop, includes Unisys computers based on a MIPS processor. IBM won the $3.5 billion FAA Advanced Automation System next-generation air traffic control system with its own RISC-chip workstation. A new IBM RISC processor, based on a custom gate array from Intel, was selected for two Navy aircraft. TRW and Honeywell were awarded parallel Air Force contracts in January 1990 for the development of a radiation-hardened 32-bit RISC computers for space systems.[57]

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[55]D. Hughes, "Sanders, Texas Instruments Develop Computer Modules for Avionics Systems," *Aviation Week & Space Technology*, February 1990, p. 117.

[56]Ibid.

[57]No byline, "TRW, Honeywell Beat IBM, Unisys for AF RISC CPU," *Electronic News*, January 29, 1990, p. 8.

Appendix C
MICROPROCESSOR DATA

Date	Mo. of Intro (Nov 71=0)	Processor	C or M	S or Co	AL or F	TL or F	Architecture	Clock (MHz)	MIPS (CISC)	MIPS (RISC)	Feature Size	No. of transistors	Price (Thn-yr)	$/MIPS (Thn-yr)	Price ($82)	$/MIPS ($82)
Jun-79	91	TI SBP9989	M				16-bit (C)	4.4	0.27				$490	$1814.8	$623	$2308.9
Jul-79	92	Mot 68000					16-bit (C)	6	0.35		2.5	68,000	$249	$711.4	$317	$905.1
Jan-80	98	Intel 8086					16-bit (C)	8	0.33			29,000				
Aug-80	105	NCR Mot68000		S	F	F	16-bit (C)	6	0.35			68,000				
Feb-81	111	Sig Mot68000			F	F	16-bit (C)	6	0.35			68,000				
Apr-81	113	Mostek M68000			F	F	16-bit	6	0.35			68,000				
May-81	114	HP/Prop		S			32-bit	18			1.5	450,000				
Jun-81	115	AT&T 32000		S			32-bit									
Jul-81	116	Fairchld 9445	M		F		16-bit	24					$200		$213	
Nov-81	120	Zilog Z8000	M				16-bit	8								
Feb-82	123	Mot 68000					16-bit	10				68,000				
Mar-82	124	Nat 16032					32-bit	10								
Apr-82	125	Honeywell LSI-6		S			16-bit									
May-82	126	Intel 80286					16-bit	8	2		2.5	130,000	$360	$180.0	$360	$180.0
Jun-82	127	AMD Int8086			F	F	16-bit	4.77	0.33		2.5	29,000				
Jul-82	128	DEC Micro/J11		S	F		16-bit	20			3					
Dec-82	133	AT&T Bellmac32A		S			32-bit (C)	3.5			3.5					
Jun-83	139	Harris 80C86	M		F		16-bit (C)	5								
Jul-83	140	HP 9000		S					1							
Aug-83	141	Zilog Z80000					32-bit (C)	10	1.5		2					
Oct-83	143	Hit 68000			F	F	16-bit (C)	12			2.6					
Apr-84	149	Nat 32032					32-bit (C)	10	0.75		3.5	70,000	$220	$293.3	$204	$272.4
May-84	150	Harris 80C88	M		F		8-bit	5			2.5		$253		$235	
Jun-84	151	Mot 68020					32-bit	12.5	2.5		2	200,000				
Jan-85	158	AT&T 32100		S			32-bit (C)	14	2.5		1.75	180,000	$500	$200.0	$451	$180.3
Feb-85	159	Mot 68020					32-bit (C)	16.67	2.5		2	200,000				
Jun-85	163	Mot 68020	M				32-bit (C)	16.67	2.5		2	200,000	$481	$192.4	$434	$173.5
Jul-85	164	Fchld F9450	M				16-bit (C)	15	0.7		3					
Oct-85	167	Fchld C100					32-bit (R)	33		6.5	2	132,000	$505	$77.7	$455	$70.1
Oct-85	167	Mot 68020					32-bit (C)	20			1.7	200,000				
Nov-85	168	TI SBR9000	M				16-bit (C)	9	0.55							
Dec-85	169	Intel 80386					32-bit (C)	12	3		1.5	275,000	$299	$99.7	$270	$89.9
Dec-85	169	Nat 32332					32-bit (C)	12.5	0.75		2.5	90,000				
Feb-86	171	IBM		S			32-bit (C)	16			2	93,000				
Apr-86	173	MIPS R2000		S		F	32-bit (R)	8		5	2	100,000				

Date	Mo. of Intro	Processor	C or M	S or Co	AL or F	TL or F	Architecture	Clock (MHz)	MIPS (CISC)	MIPS (RISC)	Feature Size	No. of transistors	Price (Thn-yr)	$/MIPS (Thn-yr)	Price ($82)	$/MIPS ($82)
Jun-86	175	MDAC MDC281	M	S			16-bit (C)	20			4		$1900		$1668	
Jun-86	175	Sig 68000			F		16-bit (C)	8					$385		$338	
Jul-86	176	TI 1750A	M		F		16-bit (C)	25	4		1.25					
Sep-86	178	Harris 80C86-RH	M		F		16-bit (C)	5					$700		$615	
Oct-86	179	NEC V60			F	F	32-bit (C)	16	3.5		1.5	325,000				
Nov-86	180	LSI L64500	M		F		16-bit (C)	25	1.5		1.5		$1800	$1200.0	$1580	$1053.6
Nov-86	180	AT&T 32200		S			32-bit (C)	24	7		1.75	172,163	$500	$71.4	$439	$62.7
Dec-86	181	Intel 80386					32-bit	16	3.5		1.5	275,000				
Dec-86	181	Toshiba Mot68020			F		32-bit (C)									
Jan-87	182	PACE 1750A	M		F		16-bit (C)	40	2.6		1.25	200,000				
Jan-87	182	Nat 32332					32-bit (C)	20	9		1.5	370,000	$565	$62.8	$480	$53.3
Feb-87	183	HP		S			32-bit (R)	8		2	1.6					
Feb-87	183	HP		S			32-bit (C)	30	15		1.5	115,000				
Apr-87	185	TI 34010					32-bit (C)	40					$500		$425	
May-87	186	Intel 80386	M				32-bit (C)				1.5					
Jul-87	188	Mot 68030					32-bit (C)	20	6		1.2	300,000				
Aug-87	189	AMD 80286			F		16-bit (C)	16					$175		$149	
Nov-87	192	Nat 32532					32-bit (C)	30	10		1.5	370,000				
Jan-88	194	GD 1750A	M	S	F		16-bit (C)	25	2		1.25	110,648				
Jan-88	194	Harris 80C286			F		16-bit	16					$181		$151	
Jan-88	194	AMD 29000					32-bit (R)	25		17		200,000	$349	$20.5	$292	$17.2
Feb-88	195	Nat 32532					32-bit (C)	30								
Mar-88	196	Mot 68030	M				32-bit (C)	20	6		1.2	300,000				
Apr-88	197	UTMC UT1750AR	M	S			16-bit (C)	12	0.7		1.5		$650	$928.6	$537	$767.4
Apr-88	197	UTMC UT1750AR	M	S			16-bit (R)	12		6	1.5		$650	$108.3	$537	$89.5
Apr-88	197	TI 34010					32-bit	50								
May-88	198	Harris 80C286	M		F		16-bit (C)	12.5					$714		$590	
Jun-88	199	Mot 88000					32-bit (R)	20		15.5						
Jun-88	199	Cyp SPARC			F		32-bit (R)	33		20	0.8		$643	$32.6	$531	$26.6
Jul-88	200	Fchld C300					32-bit (R)	50		13		165,000	$460	$35.4	$376	$28.9
Aug-88	201	Intel 80960MC	M				32-bit (R)	33		66	1	600,000	$2400	$36.4	$1960.8	$29.7
Sep-88	202	TI Cyp Sparc			F		32-bit (R)									
Oct-88	203	West 1750A	M	S	F		16-bit (C)	25			1.25					
Nov-88	204	Mot 88000					32-bit (R)	25		21	1.5		$495	$23.6	$401	$19.1
Feb-89	207	Intel 80860					64-bit (R)	40		33	1	1,000,000	$750	$22.7	$602.	$18.3
Apr-89	209	Intel 80486					32-bit (C)	25	15		1	1,200,000	$950	$63.3	$754	$50.3
Jun-89	211	BIT Sparc			F		32-bit (R)	80		50	2					
Jul-89	212	Samsung HP PA			F											
Aug-89	213	Cypress Sparc			F		32-bit (R)	40		29	0.8		$643	$22.2	$507	$17.5
Oct-89	215	AMD Am29000					32-bit (R)	33		22	1	200,000	$280	$12.7	$219	$10.0

Date	Mo. of Intro	Processor	C or M	S or Co	AL or F	TL or F	Architecture	Clock (MHz)	MIPS (CISC)	MIPS (RISC)	Feature Size	No. of transistors	Price (Thn-yr)	$/MIPS (Thn-yr)	Price ($82)	$/MIPS ($82)
Nov-89	216	AMD Int80286			F		16-bit (C)	25			1		$37		$29	
Dec-89	217	IBM America		S			32-bit (R)				1	250,000				
Dec-89	217	HP PA		S			32-bit (R)			36	0.8					
Jan-90	218	Mot 68040					32-bit (C)	25	20		0.8	1,200,000	$795	$39.8	$613	$30.7

NOTE: "C" means "commercial"; "M" means "military"; "S" means "systems-oriented"; "Co" means "component-oriented"; "AL" means "architecture leader"; "AF" means "architecture follower"; "TL" means "technology leader"; "TF" means "technology follower." For the explanation of the terms in context of this research, see Section IV.

Appendix D

DSP DATA

Date	Month of Intro	C vs M	S vs Co	L vs F	Manufac-turer	Part No.	Single chip or set (S)	Cycle Time	Throughput	No. transistors	Feature size	Power dissip.	Price (Then-yr)	$/MOPS (Then-yr)	Price ($82)	$/MOPS ($82)
	(Jun 75=0)							(ns)	(MOPS)			(mW)				
Jun-80	60				NEC	µPD7720		250				945				
Jan-82	79				TI	TMS32010		200			3.0	900	$120		$120	
Jan-82	79				AMD	29501										
Jan-82	79	M	S		Raytheon											
May-83	95				Weitek	WTL1032/22	S		5		3.0	3000				
Jan-84	103	M	S		IBM	CMAC			100		1.25	3000				
Apr-84	106	M			TI	SMJ32010		200			2.0	400				
May-84	107				Hitachi	HD61810		250	186		3.0					
May-84	107				Fujitsu	MB8764		100				300				
May-84	107				NEC					115,000	2.0					
Jun-84	108	M	S		IBM	SPE					1.25					
Jul-84	109		S		Gould AMI	S28211		50	3.3				$75	$22.73	$70	$21.10
Sep-84	111		S		AT&T	DSP32		250	8		1.5	2450	$175	$21.88	$162	$20.31
Nov-84	113				AMD	29532		100								
Dec-84	114		S		NCR	GAPP						500	$350		$325	
Feb-85	116				TI	TI32020		200	5		2.4	1200	$250	$50.00	$225	$45.09
Feb-85	116		S		ITT	UPDI01		100			2.4					
Mar-85	117		S	F	AMI	µPD7720										
May-85	119				Weitek	WTL1164/65	S	180	4							
Jun-85	120		S		AT&T	DSP32		250	12.5		2.0					
Aug-85	122	M	S		Honeywell	EOSP	S		800							
Sep-85	123				Analog Devices	ADSP3210/2 0	S		10			800				
Oct-85	124				Weitek	WTL1264/65	S		4				$795	$198.75	$717	$179.22
Jan-86	127		S	F	Gen Instr	DSP32010		200	5		2.4		$59	$11.80	$52	$10.36
Feb-86	128				NEC	µPD77230		150		370,000	1.75					
Apr-86	130				Weitek	WLT2164/65	S	160	32			1000				
Apr-86	130		S		Thomson	TS68930		160		120,000	2.0	1500	$150		$132	
Apr-86	130		S		Philips	PCB5010		125	48			500				
May-86	131				TI	TMS32025		100			1.8	1400	$134		$118	
Jun-86	132				Inmos	IMS A100						1500	$406		$356	
Jun-86	132				Weitek	WTL7137/36	S	90	24		1.5	2000	$385	$16.04	$338	$14.08
Jun-86	132				Analog Devices	ADSP2100		125			1.5	500	$375		$329	
Jul-86	133				Zoran	ZR34161		100		70,000	2.0	500	$700		$615	
Aug-86	134				National Semi	LM32900		100			2.0	500	$100		$88	
Aug-86	134	M			National Semi	LM32900		100			2.0	500	$250		$219	
Sep-86	135				Oki	MSM6992		100	20		2.0	500	$250	$12.50	$219	$10.97
Jan-87	139				Plessey	PDSP1601/1 0/30/40	S						$525		$446	
Jan-87	139				TI	TMS320E15		200					$60		$51	
Feb-87	140				BIT	B3110/20	S			128,000		7800	$640		$544	
Mar-87	141		S		AT&T	DSP16		75		140,000	1.0	500	$55		$47	
Mar-87	141				Motorola	DSP56001		100			1.5		$500		$425	
Apr-87	142	M			TI	SMJ32020		200								
May-87	143		S	F	Gen Instr	DSP320EE12		195					$100		$85	

Date	Month of Intro	C vs M	S vs Co	L vs F	Manufacturer	Part No.	Single chip or set (S)	Cycle Time	Throughput	No. transistors	Feature size	Power dissip.	Price (Then-yr)	$/MOPS (Then-yr)	Price ($82)	$/MOPS ($82)
Jun-87	144															
Jul-87	145				Analog Devices	ADSP3212/22	S	50	40		1.0	2000	$594	$14.85	$505	$12.62
Sep-87	147				Zoran	ZR34325		80	37.5		2.0		$490	$13.07	$416	$11.10
Oct-87	148				Hitachi	HD81810		50			1.3					
Nov-87	149	M			TI	TMS320E15		200					$60		$51	
Jan-88	151	M			TI	SMJ32025		80			1.8	1020				
Feb-88	152				TI	TMS320C30		60	33	700,000	1.0		$1300	$39.39	$1089	$32.99
Feb-88	152				Analog Devices	ADSP2100A										
Mar-88	153				TI	74ACT8847		35	29		1.0		$450	$15.52	$377	$13.00
Mar-88	153				NEC	PD77230		150	13.4							
Mar-88	153				Weitek	WTL3164		100	20	166,000	1.25		$829	$41.45	$694	$34.72
Apr-88	154			F	Microchip	DSP320C10-32			8				$27	3.38	$22	$2.79
Apr-88	154				BIT		S		60				$490	$8.17	$405	$6.75
May-88	155				AMD	Am29C327		100	10	250,000	1.2		$595	$59.50	$492	$49.18
Jun-88	156		S		Honeywell	HDSP66110/210	S		500		1.2					
Jun-88	156	M	S		Honeywell	HDSP66110/210	S		500		1.2		$1300	$2.60	$1074	$2.15
Jun-88	156		S		AT&T	DSP32C		80	25		0.75		$325	$13.00	$269	$10.74
Sep-88	159				Inmos	IMS A110			400	400,000		2000	$500	$1.25	$408	$1.02
Oct-88	160															
Oct-88	160				Fujitsu	MB86232		75	6.7		1.3		200	29.85	162	24.21
Oct-88	160				Oki	MSM699210			20		1.5					
Dec-88	162	M	S		UTMC	IQ-MAC			87.5			2000	$1850	$21.14	$1500	$17.15
Jan-89	163				Motorola	DSP96000		75	40				$500	$12.50	$402	$10.04
Aug-89	170				Motorola	DSP96002			27				$750	$27.78	$591	$21.89
Oct-89	172	M			Analog Devices	ADSP2100AU		80					$462		$361	
Feb-90	176	M	S		TRW/ Motorola	CPUAX			200	4,000,000	0.5	17000				

NOTE: "C" means "commercial"; "M" means "military"; "S" means "systems-oriented"; "Co" means "component-oriented"; "L" means "leader"; "F" means "follower." For the explanation of the terms in context of this research, see Section V.

Appendix E
SRAM DATA

Date	No. of Intro. (Jan 79=0)	C vs M	S vs. Co	L vs F	Manufacturer	Part No.	Capacity	Access time (ns) by organization by 1	by 4	by 8	by 9	by 16	Org. unk.	Power Dissip. (mW)	Speed-Power Product	Feature Size (µm)	Price (Then-yr)	$/bit (Then-yr)	Price ($82)	$/bit ($82)
Jan-80	13				Intersil	1M7147L-3	4096		55											
Feb-80	14				Fujitsu	MB8414E	4096		250					68	17000					
Feb-80	14		S		IBM		16384	45						225	10125	2.5				
Jun-80	18				Mostek	MK4802	16384						70	690	48300					
Jun-80	18				Harris	6564	65536						350	300	105000					
Jul-80	19				Intel	2147H	4096		35					900	31500					
Aug-80	20	M			Intel	2148H	4096		70								$82.50	$0.02014	$96.27	$0.02350
Sep-80	21	M			Mostek	MKB4118	8192			150				400	60000		$31.95	$0.00390	$37.28	$0.00455
Jan-81	25				Mostek	MK4147	4096						55	500	27500					
Feb-81	26				Intel	2167	16384	55									$68.55	$0.00418	$72.93	$0.00445
Mar-81	27				Nippon		16384						25	575	14375	1.5				
Apr-81	28			F	Fujitsu	MBM2148	4096		55											
Apr-81	28				NEC	uPD446C/D	16384			150							$20.00	$0.00122	$21.28	$0.00130
Aug-81	32				IDT	6116	16384			70				180	12600		$90.00	$0.00549	$95.74	$0.00584
Sep-81	33	M	S		GTE	M8104	8192							165			$67.50	$0.00824	$71.81	$0.00877
Sep-81	33			F	Hitachi	HM6167	16384	70						150	10500	2.0				
Sep-81	33				TI	TMS2149	4096		35					660	23100					
Oct-81	34				Inmos	IMS1420	16384		45					600	27000		$38.00	$0.00232	$40.43	$0.00247
Dec-81	36	M			Harris	HS6504RH	4096	250						100	25000		$400.00	$0.09766	$425.53	$0.10389
Jan-82	37	M		F	Synertek	SYM2149H	4096		55											
Feb-82	38	M	S		RCA	CMM5104/RZ	4096	180												
Mar-82	39	M		F	TI	SMJ2147	4096	55												
May-82	41				Nat Semi	NMC2116	16384			250				375	93750					
Jun-82	42	M			Harris	HM6504B	4096	100								2.0				
Jul-82	43				Synertek	SY2114AL	4096		100											
Aug-82	44			F	IDT	6167	16384	45						150	6750	2.5				
Nov-82	47		S		RCA	CDM6116E-2	16384			200										
Jan-83	49	M		F	IDT	6168	16384		45								$40.00	$0.00244	$38.50	$0.00235
Feb-83	50				Fairchild		16384	25								2				
Feb-83	50				Toshiba	TC5565P	65536			100				275	27500		$85.00	$0.00130	$81.81	$0.00125
Jul-83	55				IDT		16384			85										
Jul-83	55	M		F	Mostek	MKB6116	16384			200							$46.70	$0.00285	$44.95	$0.00274
Aug-83	56	M			Harris		16384			70										
Sep-83	57				Synertek	SY2130	8192			100							$35.00	$0.00427	$33.69	$0.00411
Nov-83	59				Motorola		16384	35												
Dec-83	60	M			ICI	64-01M	65536										$189.00	$0.00288	$181.91	$0.00278
Mar-84	63	M			EDI	EDH8808	65536			85				275	23375		$423.00	$0.00645	$392.76	$0.00599
May-84	65				AMD		16384		45					440	19800	2.5				
Jun-84	66				Inmos		16384		35					500	17500	2				
Jul-84	67				Toshiba		16384		35											
Nov-84	71	M			TI		73728				35			450	15750	1.25				
Jan-85	73				Fairchild	F1600	65536	45						200	9000	2.0	$90.00	$0.00137	$81.15	$0.00124
Apr-85	76				AMD		16384	15												
Apr-85	76				Cypress		16384									1.2				
Jun-85	78				NEC	µPD43256C	256000			120				350	42000	1.2	$98.50	$0.00038	$88.82	$0.00035
Jul-85	79					V64H1	65536						35	500	17500	1.5				
Jul-85	79				Harris	HM-65262	16384	55									$24.10	$0.00147	$21.73	$0.00133
Jul-85	79				Hitachi	HM6787	65536	25						300	7500		$68.50	$0.00105	$61.77	$0.00094
Aug-85	80	M			Harris	HS65262	16384	70									$67.07	$0.00409	$60.48	$0.00369
Sep-85	81	M	S		RCA	CDM5114C/ D3	4096										$32.00	$0.00781	$28.85	$0.00704
Sep-85	81				Fairchild	F1600	65536	45						200	9000					
Oct-85	82				VLSI	VT64KS4	65536						35	350	12250	2.0	$115.00	$0.00175	$103.70	$0.00158
Nov-85	83				Motorola	MCM6164	65536			45				400	18000	1.5	$30.00	$0.00046	$27.05	$0.00041
Jan-86	85				NEC	µPD4362	65536		45								$55.00	$0.00084	$48.29	$0.00074
Feb-86	86				AMD	Am99CL88	65536			70				220	15400		$93.60	$0.00143	$82.18	$0.00125
Feb-86	86	M			AMD	Am99C88	65536			70				330	23100		$245.00	$0.00374	$215.10	$0.00328
Mar-86	87				Hitachi		16384		4					4400	17600	1.25				
Apr-86	88				Cypress	CY7C150	4096						15				$29.40	$0.00718	$25.81	$0.00630
May-86	89	M			Performance		65536		20					550	11000	1.25				
Jun-86	90	M			Cypress	CY7C150	4096						25			0.8	$65.05	$0.01588	$57.11	$0.01394
Jun-86	90				AMD	Am99C641	65536	35						715	25025		$50.75	$0.00077	$44.56	$0.00068

Date	No. of Intro.	C vs M	S vs. Co	L vs F	Manufacturer	Part No.	Capacity	Access time (ns) by organization: by 1	by 4	by 8	by 9	by 16	Org. unk.	Power Dissip.	Speed-Power	Feature Size	Price (Then-yr)	$/bit (Then-yr)	Price ($82)	$/bit ($82)
Jun-86	90				Intel	51C66-25	16384	25								1.5				
Jul-86	91				Motorola	MCM6287	65536		35					250	8750	1.5	$54.60	$0.00083	$47.94	$0.00073
Jul-86	91			F	Mostek	MK41H68	16384		20					250	5000		$34.30	$0.00209	$30.11	$0.00184
Jul-86	91	M			Harris	HS-65262RH	16384	100									$800.00	$0.04883	$702.37	$0.04287
Aug-86	92				VLSI	VT16DP8	16384						60				$52.60	$0.00321	$46.18	$0.00282
Aug-86	92				Fujitsu		65536						35	459	16065	1.3				
Aug-86	92				Fujitsu		262114						55	550	30250	1.3				
Aug-86	92				AMD	Am99C59	16384		10					770	7700		$24.75	$0.00151	$21.73	$0.00133
Oct-86	94				Lattice	SR64K8	65536			35				450	15750		$59.85	$0.00091	$52.55	$0.00080
Oct-86	94				MOS	M562256	262114			55				300	16500	1.2	$95.00	$0.00036	$83.41	$0.00032
Nov-86	95	M	S		RCA	CMM6167/1RZ	16384						105			3.0	$1000.00	$0.06104	$877.96	$0.05359
Nov-86	95				AMD	99C328	262114			35				400	14000	1.2				
Dec-86	96				Cypress		65536						25	550	13750	0.8				
Dec-86	96				Toshiba	TMM2089C	73728				35						$36.80	$0.00050	$32.31	$0.00044
Jan-87	97				RCA	CDM62256	262114			100							$50.00	$0.00019	$42.48	$0.00016
Apr-87	100				Performance	P4C187	65536	12									$61.00	$0.00093	$51.83	$0.00079
May-87	101				Hitachi	HM10490CG	65536	7						320	2240		$68.00	$0.00104	$57.77	$0.00088
May-87	101				Mitsubishi	M5M5257	262114		35								$152.00	$0.00058	$129.14	$0.00049
Jun-97	102				Saratoga	SSM7188	65536		25								$41.00	$0.00063	$34.83	$0.00053
Jun-87	102				IDT		65536			35										
Sep-87	105	M			Intel	M51C98	65536						35				$150.00	$0.00229	$127.44	$0.00194
Sep-87	105				IDT	IDT71586	65536					35					$34.50	$0.00053	$29.31	$0.00045
Dec-87	108	M			Harris	HM65642	65536										$160.35	$0.00245	$136.24	$0.00208
Jan-88	109				Saratoga	SSM7174	65536			25							$42.50	$0.00065	$35.59	$0.00054
Feb-88	110				IDT	7198	65536		15							0.9	$82.80	$0.00126	$69.35	$0.00106
Mar-88	111				IDT	71502	65536					35		900	31500		$38.50	$0.00059	$32.24	$0.00049
Mar-88	111				IDT	IDT100490	65536	15						320	4800	1.5	$86.67	$0.00132	$72.59	$0.00111
Apr-88	112				IDT	7174	65536			45										
Jun-88	114				Nat Semi		262114	15												
Jul-88	115				Toshiba	TC551001	1048576			100										
Nov-88	119	M			Cypress	CY7C194	262114		35											
Nov-88	119				Cypress	CY7C187	65536	20						440	8800					
Dec-88	120				Hitachi		262114		20											
Jan-89	121	M			Intel	M51C98	65536									1.25				
Feb-89	122				Mosaic	MSM8128	1048576			70										
Feb-89	122				Hitachi	HM624256	1048576													
May-89	125				Motorola	MCM6206	262114			20						1.2				
Jun-89	126				Motorola	MCM60256APC	262114			100				275	27500					
Jul-89	127				ILC	MEM84102	1048576					55					$898.00	$0.00086	$707.64	$0.00068
Sep-89	129				Paradigm	PDM41258	262114		20					400	8000		$147.05	$0.00056	$115.88	$0.00044
Oct-89	130				Micron	MT5C2565	262114		20					1000	20000					
Nov-89	131	M			Micron	MT5C2564	262114		25					1000	25000					
Dec-89	132				Mitsubishi		1048576		35							0.7	$195.00	40.00019	$152.46	$0.00015
Dec-89	132	M			Paradigm	PDM41258	262114													
Jan-90	133	M			VLSI	VM62832	262114			45							$150.00	$0.00058	$115.65	$0.00044

NOTE: "C" means "commercial"; "M" means "military"; "S" means "systems-oriented"; "Co" means "component-oriented"; "L" means "leader"; "F" means "follower." For the explanation of the terms in context of this research, see Section VI.

Appendix F
PROM DATA

Date	Mo. Intro (Jun 71=0)	C vs. M	S vs. Co	L vs. F	Manufact.	Part No.	Type	Capacity	Access time (ns) by organization: by 1	by 4	by 8	by 16	Org. Unk	Power Dissip. (mW)	Feature Size	Price (Thn-yr)	$/bit (Thn-yr)	Price ($82)	$/bit ($82)
Nov-79	100				Motorola		EPROM	32768											
Jan-80	102				Intel	2732A	EPROM	32768					200	750		$57.00	$0.00174	$66.51	$0.00203
Jan-80	102		S		RCA	CDP18U42	EPROM	2048			1000			20		$28.40	$0.01387	$33.14	$0.01618
Jun-80	107				TI	TBP28R166	PROM	16384					20	550					
Jun-80	107				Motorola	MCM68764	EPROM	65536					350	660					
Jul-80	108				Hitachi	HN48016	EEPROM	16384					300	300					
Aug-80	109				Intel	2764-2	EPROM	65536					200	750		$163.00	$0.00249	$190.20	$0.00290
Sep-80	110				Harris	HM-7681A	PROM	8192			50					$36.00	$0.00439	$42.01	$0.00513
Oct-80	111	M	S		Hughes	HNVM 3008	EEPROM	8192			500			5					
Oct-80	111				Xicor	2201	EEPROM	1024	300					200					
Nov-80	112				Nat Semi	67C16	EPROM	16384					300						
Jan-81	114				TI	TMS2564-35	EPROM	65536			350			400	3.5	$147.00	$0.00224	$156.38	$0.00239
Feb-81	115	M	S		Hughes		PROM	4096					200						
Feb-81	115				Harris	HM-6641	PROM	4096					200			$28.71	$0.00701	$30.54	$0.00746
Feb-81	115	M			Intel	M2732	EPROM	32768					450	750		$134.05	$0.00410	$142.61	$0.00435
May-81	118				Intel	3636B	PROM	16384			35			800		$50.00	$0.00306	$53.19	$0.00324
Jun-81	119				AMD	27S40	PROM	16384		35						$44.95	$0.00274	$47.82	$0.00292
Jul-81	120	M	S		NCR	52832	EEPROM	32768			200			160		$39.60	$0.00121	$42.13	$0.00129
Sep-81	122				Intel		PROM	32768					35						
Sep-81	122		S		Gen Instr	ER5716	EEPROM	16384			300								
Oct-81	123				Harris	HM176641-5	PROM	65536					85	950	3.0	$150.00	$0.00229	$159.57	$0.00243
Oct-81	123		S		Hughes	HNV3704	EEPROM	8192			550					$67.60	$0.00826	$71.91	$0.00878
Nov-81	124				TI	TMS2528	EPROM	131072			250			400	3.0				
Feb-82	127				Harris	HM76321	PROM	32768			63					$100.00	$0.00305	$100.00	$0.00305
Feb-82	127				Intersil	IM6657A	EPROM	8192		300									
Feb-82	127	M			Harris	HM76321	PROM	32768			63								
Mar-82	128				Intel	2817	EEPROM	16384						850					
Mar-82	128	M			TI	SMJ2564	EPROM	65536			450								
Apr-82	129	M			Harris	HM-76641	PROM	65536					100						
May-82	130				Intel	27128	EPROM	131072					250	300		$93.00	$0.00071	$93.00	$0.00071
May-82	130				Nat Semi	NMC27C32	EPROM	32768					350						
May-82	130				Motorola	MCM76161	PROM	16384					70			$18.85	$0.00115	$18.85	$0.00115
Jun-82	131				Motorola	MCM2816	EEPROM	16384			350			500					
Aug-82	133				Motorola	MCM2832	EEPROM	32768					150			$150.00	$0.00458	$150.00	$0.00458
Sep-82	134				AMD	Am2764	EPROM	65536											
Oct-82	135				Fairchild		PROM	16384							3.0				
Nov-82	136	M	S		Hughes	HM3008	EEPROM	8192								$84.00	$0.01026	$84.00	$0.01026
Jan-83	138		S	F	Rockwell	D5213	EEPROM	16384											
Mar-83	140				Nat Semi	DM77187S	PROM	16384			35								
Mar-83	140				Fujitsu		EPROM	262144					250	158		$126.00	$0.00048	$121.27	$0.00046
Apr-83	141				Seeq		EEPROM	65536					250		2.0				
May-83	142		S		NCR	52832	EEPROM	32768			300				4.0	$39.62	$0.00121	$38.13	$0.00116
May-83	142				AMD	Am27128	EPROM	131072			150			525		$88.40	$0.00067	$85.08	$0.00065
May-83	142	M			AMD	Am27128	EPROM	131072			200			525		$365.00	$0.00278	$351.30	$0.00268
May-83	142				Intel	27256	EPROM	262144					200	550	2.0	$87.00	$0.00033	$83.73	$0.00032
Jun-83	143				Monolith. Mem	6353281A	PROM	32768			40			750		$54.96	$0.00168	$52.90	$0.00161
Jun-83	143				Xicor	X2864A	EEPROM	65536			300					$89.00	$0.00136	$85.66	$0.00131
Jun-83	143				Fairchild	93Z564	PROM	65536			55			120	4.0	$50.00	$0.00076	$48.12	$0.00073
Jun-83	143	M			Fairchild	93Z564	PROM	65536			65				4.0				
Jun-83	143				Fujitsu		PROM	65536					40	770	4.0	$50.00	$0.00076	$48.12	$0.00073
Jun-83	143				Harris		PROM	65536					80	900	5.0	$100.00	$0.00153	$96.25	$0.00147
Jun-83	143				AMD		EPROM	262144					170	525	2.5	$344.00	$0.00131	$331.09	$0.00126
Sep-83	146				Nat Semi	NMC9817	EEPROM	16384			250			750		$40.00	$0.00244	$38.50	$0.00235
Jan-84	150				Inmos		EEPROM	65536					200	825	2.7				
Apr-84	153	M			AMD	Am27512	EPROM	524288			450				2.0				
Apr-84	153				AMD	Am27512	EPROM	524288			250			525	2.0	$395.60	$0.00075	$367.32	$0.00070
Jun-84	155	M	S		NCR	52864	EEPROM	65536					450			$324.00	$0.00494	$300.84	$0.00459
Jun-84	155		S		Thomson-CSF		EPROM	262144					150	400	1.7				
Jul-84	156		S		NCR	52864	EEPROM	65536					300			$294.00	$0.00449	$272.98	$0.00417
Aug-84	157				Intel	27128A	EPROM	131072			150					$36.80	$0.00028	$34.17	$0.00026

Date	Mo. Intro	C vs. M	S vs. Co	L vs. F	Manufact.	Part No.	Type	Capacity	Access time (ns) by organization: by 1	by 4	by 8	by 16	Org. Unk	Power Dissip.	Feature Size	Price (Thn-yr)	$/bit (Thn-yr)	Price ($82)	$/bit ($82)
Jan-85	162				Hitachi	NM27256G-25	EPROM	262144					250			$63.00	$0.00024	$56.81	$0.00022
Feb-85	163				Nat Semi		EPROM	262144					200						
May-85	166				Cypress	CY7C291	PROM	16384			35			500					
May-85	166	M	S		Raytheon	39VP864	PROM	65536			55								
May-85	166		S		Raytheon	29VP864	PROM	65536			55								
May-85	166				Fairchild	93Z565A	PROM	65536			45			900					
May-85	166				AMD	Am27S49A	PROM	65536			40								
May-85	166				AMD	Am27C10024	EPROM	1048576				170		250					
Jun-85	167				Intel	27C256	EPROM	262144					170			$32.40	$0.00013	$29.22	$0.00011
Jul-85	168				NEC	µPD27C256	EPROM	262144					150	150		$20.65	$7.88E-05	$18.62	$7.10E-05
Aug-85	169				Fujitsu	MBM27C512	EPROM	524288					250	50		$50.00	$9.54E-05	$45.09	$8.60E-05
Nov-85	172				AMD	Am27S51	PROM	131072			35								
Jan-86	174				Motorola	MCM2864	EEPROM	65536							2.0				
Jan-86	174				Seeq	M28C256	EEPROM	262144											
Jan-86	174				Xicor	X28256	EEPROM	262144							2.0				
Feb-86	175		S		Gen Instr		EEPROM	65536							1.5				
Mar-86	176				AMD	Am27C1024	EPROM	1048576				170		250	1.5	$199.00	$0.00019	$174.71	$0.000167
Apr-86	177				Intel	27010	EPROM	1048576			200				1.4	$112.30	$0.00011	$98.60	$9.40E-05
Apr-86	177				NEC		EPROM	1048576				150			1.2	$55.00	$5.25E-05	$48.29	$4.61E-05
Jul-86	180				Toshiba	TC571000D	EPROM	1048576			150								
Jul-86	180	M			VLSI Tech	VM27C256	EPROM	262144					250			$243.00	$0.00093	$213.35	$0.00081
Aug-86	181				WaferScale	WS57C64F	EPROM	65536			55			300					
Aug-86	181				Cypress	CY7C261	EPROM	65536			35			500					
Aug-86	181				Seeq	48128	EEPROM	131072			#N/A				2.5				
Sep-86	182				White Tech	8023	EEPROM	262144					250			$588.40	$0.00224	$516.59	$0.00198
Oct-86	183				Exel		EEPROM	262144					300						
Oct-86	183				Exel		PROM	16384					55						
Dec-86	185				Motorola	NCM10149L10	PROM	1024		7				700		$28.50	$0.02783	$25.02	$0.02444
Jan-87	186				WaferScale	WS27C56F	PROM	262144			70			300	1.2	$82.00	$0.00031	$69.67	$0.00027
Apr-87	189				Seeq	48C512	EEPROM	524228			200				1.2	$33.00	$6.29E-05	$28.04	$5.35E-05
May-87	190	M			Xicor	X28C256	EEPROM	262144											
Jun-87	191				Cypress	CY7C251	PROM	131072			45			550	1.2	$99.20	$0.00076	$84.28	$0.00064
Jun-87	191				Seeq	36C32	EPROM	32768			35			350	1.25	$18.50	$0.00056	$15.72	$0.00048
Jul-87	192				WaferScale	WS57C257	EPROM	262144			55			300	1.2	$94.00	$0.00036	$79.86	$0.00030
Jul-87	192				Catalyst/ Oki	MSM28C64A	EEPROM	65536					120	50	1.5				
Nov-87	196				TI	TMS27C292	EPROM	16384			35			394	2.0				
Nov-87	196			F	Catalyst/ Oki	CAT27C210	EPROM	1048576			200								
Nov-87	196			F	Mitsubishi	M5M27C102K	EPROM	1048576				#N/A				$40.75	$3.89E-05	$34.62	$3.30E-05
Nov-87	196	M			Seeq	28C256	EEPROM	262144											
Dec-87	197				Gen Instr	27HC64	EPROM	65536			70					$21.50	$0.00033	$18.27	$0.00028
Jan-88	198				Exel	XL46HC64	PROM	65536					35			$33.00	$0.00050	$27.64	$0.00042
Feb-88	199				Seeq	48F512	EEPROM	524288			250				1.5	$18.75	$3.58E-05	$15.70	$3.00E-05
Mar-88	200				Intel	27F256	EEPROM	262144			170				1.5	$29.90	$0.00011	$25.04	$9.55E-05
Apr-88	201				Seeq	48C512	EEPROM	524288			#N/A				1.2	$33.00	$6.29E-05	$27.27	$5.20E-05
Jun-88	203				Intel		EPROM	4194304				90		100	1.0				
Sep-88	206				Toshiba		EPROM	262144			70								
Oct-88	207				Fujitsu	MB71C46	PROM	131072					30	200					
Nov-88	208				Cypress	CY7C261	PROM	65536			30			550	1.2	$43.90	$0.00067	$35.60	$0.00054
Dec-88	209	M			Cypress	CY7C261	PROM	65536			45			660	1.2				
Jan-89	210				Toshiba		EEPROM	262144					170	360					
Feb-89	211				Mitsubishi	M5M27C100K-12	EPROM	1048576					120			$35.00	$3.34E-05	$28.11	$2.68E-05
Mar-89	212				Seeq	48F010	EEPROM	1048576			250				1.5	$92.00	$8.77E-05	$73.90	$7.05E-05
Mar-89	212				Seeq	27F010	EPROM	1048576			250				1.5	$78.75	$7.51E-05	$63.25	$6.03E-05
Apr-89	213				Intel	27F256	EEPROM	262144			250			150	1.5	$19.90	$7.59E-05	$15.81	$6.03E-05
Jun-89	215				WaferScale		EPROM	4194304					120		1.2				
Jul-89	216				Xicor	X28C010	EEPROM	1048576			200			400		$995.00	$0.00095	$784.08	$0.00075
Aug-89	217				Cypress	CY7C271	EPROM	262144			45			660	0.8	$123.50	$0.00047	$97.32	$0.00037
Aug-89	217				Intel	27C240	EPROM	4194304				200		450		$140.00	$3.34E-05	$110.32	$2.63E-05
Aug-89	217				Atmel	AT28C1024	EEPROM	1048576			120			500		$750.00	$0.00072	$591.02	$0.00056
Aug-89	217				White Tech.	WE-256KB-150	EEPROM	2097152			150			450		$1925.00	$0.00092	$1516.94	$0.00072
Sep-89	218				Toshiba	TC574000D	EPROM	4194304			150			450		$110.00	$2.62E-05	$86.68	$2.07E-05
Sep-89	218	M			WaferScale	WS27C512DM	EPROM	524288			120					$29.30	$5.59E-05	$23.09	$4.40E-05
Dec-89	221				Int'l CMOS	27CX010	EPROM	1048576			55			500		$98.00	$9.35E-05	$76.62	$7.31E-05

Date	Mo. Intro	C vs. M	S vs. Co	L vs. F	Manufact.	Part No.	Type	Capacity	Access time (ns) by organization by 1	by 4	by 8	by 16	Org. Unk	Power Dissip.	Feature Size	Price (Thn-yr)	$/bit (Thn-yr)	Price ($82)	$/bit ($82)
Dec-89	221				AMD	Am27C020	EPROM	2097152			100					$99.45	$4.74E-05	$77.76	$3.71E-05
Jan-90	222	M			Seeq	48F512	EEPROM	524288											
Jan-90	222	M			Cypress	CY7C271	EPROM	262144			55			715	0.8				
Jan-90	222				Philips/ Signetics	27C210	EPROM	1048576				200			1.0	$20.40	$1.95E-05	$15.73	$1.5E-05

NOTE: "C" means "commercial"; "M" means "military"; "S" means "systems-oriented"; "Co" means "component-oriented"; "L" means "leader"; "F" means "follower." For the explanation of the terms in context of this research, see Section VII.

Appendix G
MORE ABOUT STATISTICS

This appendix provides greater details on the statistical analysis appearing in Sections IV through VII.

Time was an important dimension of this study. Individual IC characteristics were plotted versus time to compare the advances made by manufacturers in different segments of the industry. To determine whether different trade-offs between component characteristics were made by different types of manufacturers, an integrative analysis was required. Multivariate regression was used as methodology for this analysis. A series of regression equations was constructed for each component group in order to determine best fit to the data. All equations were of the form

$$\text{Month of Introduction} = \alpha + \beta^*(\text{Char 1}) + \gamma^*(\text{Char 2}) + \ldots + \delta^*(\text{Dummy 1}) + \varepsilon^*(\text{Dummy 2})\ldots$$

where Char 1, Char 2, etc. were either IC characteristics (e.g., clock speed, feature size) or transforms of these characteristics (e.g., Natural Logarithm of No. of Transistors). Dummy variables were used for non-quantitative variables (e.g., commercial vs. military, rad-hard vs. non-rad-hard).

A microcomputer-based statistical package was used to generate parameters in the equation. Various models and the parameters generated by the statistics package were presented in tables in Sections IV through VII. The statistics package tested the significance of the generated parameters. A t-statistic was generated for each regression coefficient, testing that coefficient against zero (i.e., the null hypothesis was that the coefficient equals zero; alternate hypothesis that it was not equal to zero). A one-tailed significance level for each t-value was shown. Rather than define an arbitrary rejection level for the null hypothesis (e.g., 5 percent), I chose to show the significance level generated by the statistics package, so that the choice of whether a given parameter was significant could be left to the reader. Since the regression analysis was not used for predicting future introduction dates of ICs, but rather as a means of establishing a different viewpoint on the past introduction dates, I tended to view any significance statistic below 10 percent as acceptable.

Another statistic of interest is R^2, the percentage of variance in the data which can be explained by the model. I used Adjusted R^2 as the statistic of interest. Use of this statistic, rather than R^2, eliminates the concern that model fit to the data is improved simply by reducing degrees of freedom with additional regressors rather than by explaining variation in the data.

In some cases the number of complete observations was insufficient to provide a reasonable number of degrees of freedom in the regression. The missing data were then "filled in," using the following method. An equation of the form

$$\text{Char } 1 = \alpha + \beta^*(\text{Month of Introduction}).$$

The resulting equation was used to calculate missing data for the IC characteristic in question. The variables which contain "filled-in" data are clearly marked in the discussion of regression analysis in the body of the text.

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